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A STATISTICAL STUDY OF BREAKOUTS IN OIL-WELLS IN ALBERTA

by

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ABSTRACT

Breakouts or preferred directional spalling along the walls of boreholes have been observed in many wells throughout the sedimentary basin in most parts of Alberta. Many studies have been carried out into the possible cause of this phenomenon. In this study, data focussing on the relationship of breakouts with depth, rock types and age of the rocks have been investigated in 50 wells scattered through most parts of Alberta plus one well in British Columbia. A regression of breakout azimuths on depths shows regression coefficients not significantly different from zero. Furthermore, it has been noted that breakouts have no relation with the rock types and the age of the rocks. The breakout azimuths in a well are tightly grouped around a mean direction which, in most cases, is NW-SE.

These observations and other evidences lead to the conclusion that breakout formations are better explained by the stress concentration at the walls of the boreholes, rather than the result of the drill encountering pre-existing fractures or zones of weaknesses. From this conclusion, the orientation of the smaller horizontal principal stress is NW-SE and the larger horizontal principal stress is NE-SW. The consistency of the breakout azimuths with depth, wherever these phenomena are observed, may imply that such large horizontal principal stresses are not necessarily limited to the top crustal sedimentary rocks but may be continued down into the deep and older

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Breakouts or preferred directional spalling along the walls of boreholes have been observed in many wells throughout the sedimentary basin in most parts of Alberta. Many studies have been carried out into the possible cause of this phenomenon. In this study, data focussing on the relationship of breakouts with depth, rock types and age of the rocks have been investigated in 60 wells scattered through most parts of Alberta plus one well in British Columbia. A regression of breakout azimuths on depths gives regression coefficients not significantly different from zero. Furthermore, it has been noted that breakouts have no relation with the rock types and the age of the rocks. The breakout azimuths in a well are tightly grouped around a mean direction which, in most cases, is NW-SE.

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Precambrian igneous rocks of the Earth's crust.

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I. THE PHENOMENON OF ALIGNED BREAKOUTS AND ITS MEANING

The primary purpose of borehole dipmeter surveys is to determine magnitudes and azimuths of dips of bedding planes from observations in a single hole. Prior to such surveys, the subsurface structural picture was determined primarily from seismic sections and correlation of marker horizons between three or more wells not drilled on a straight line. Unfortunately, geophysical surveys normally cover large areas and are good for determination of average regional dips but give poor resolution of local dip variations. In a like manner dip determination of marker horizons from correlation is valid only if the bed used is truly a plane surface and continuous between wells.

About 1970 the **Four Arm Dipmeter** (also known as **The High Resolution Dipmeter, HDT**) began to supersede the three arm type of tool. This thesis is largely concerned with oil-wells of non-circular section. Figure 1 reveals that the HDT is capable of determining two different diameters of a non-circular hole and their azimuths, whereas the three arm instrument cannot do this.

In the four arm dipmeter shown in Figure 2, the four arms are azimuthally spaced 90° apart. Each spring loaded arm carries a pad of electrodes which enables the electrical resistivity of the rock near the electrodes to be recorded. The four correlation curves in Figure 3 show typical resistivity variations which enable beds to be recognised and correlated. A plane can be fitted to the four depth

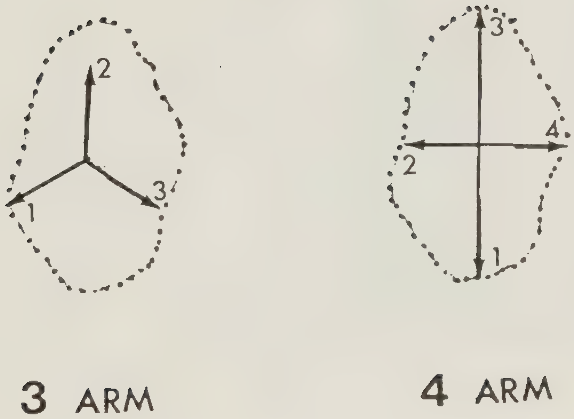


Figure 1.... Possible positions assumed by 3-arm caliper and 4-arm dual calipers in the same elongated hole. (schematic)

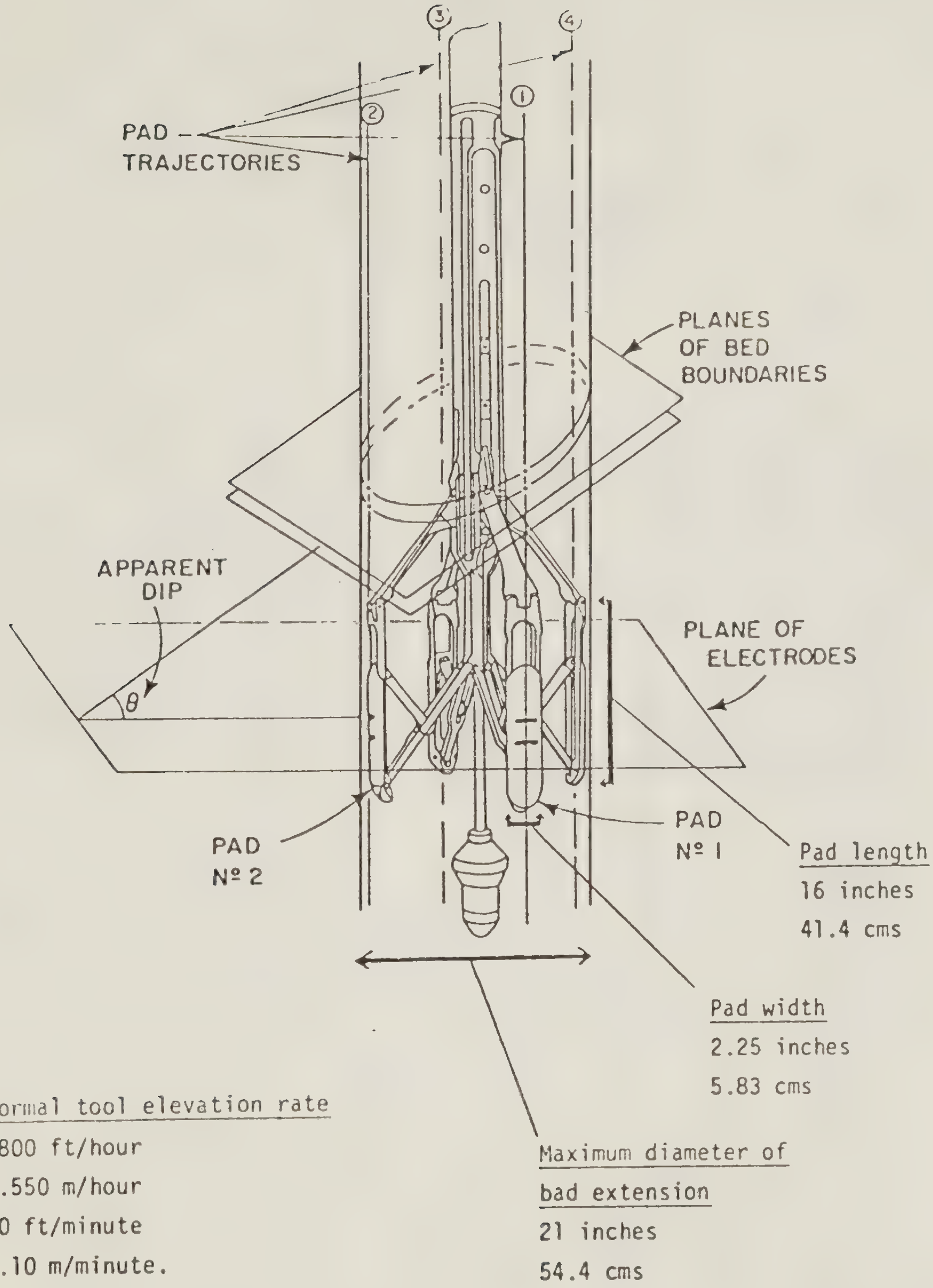


Figure 2.... Schlumberger 4-arm dipmeter tool.(courtesy of J. Cox)

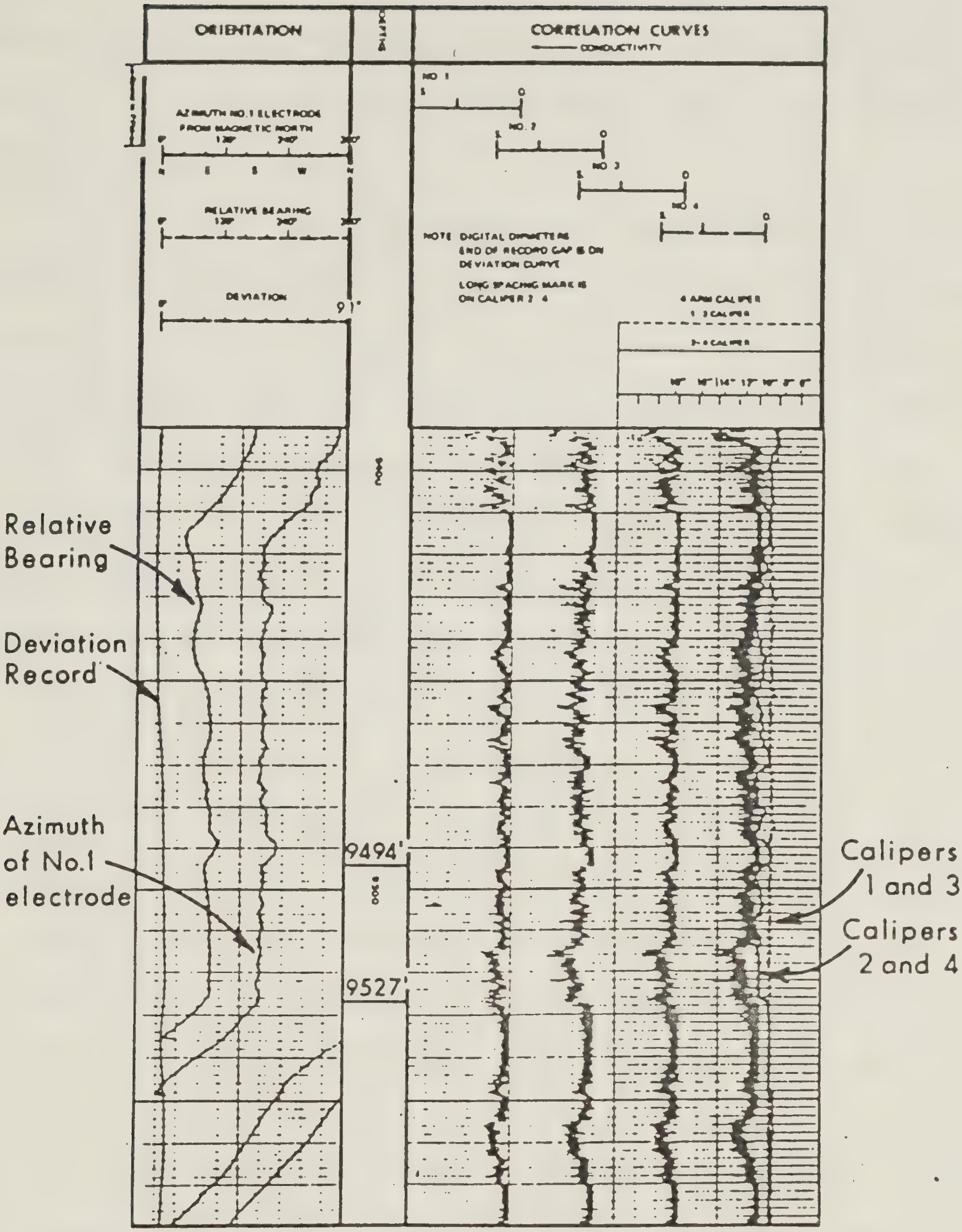


Figure 3.... Typical 4-arm dipmeter log record

values for a bed to give its dip in magnitude and direction. Resistivity changes on only one or two electrode pads may assist in identifying fractures as is illustrated schematically in figure 4.

Traces not yet discussed in figure 3 are of principal interest in this study. On the far right the two orthogonal diameters indicated by opposed pairs of calipers are recorded. These provide information concerning the shape of the borehole. On the left we require the trace which shows the azimuth of No.1 electrode, relative to a magnetic compass housed in the tool. Other traces on the left are;

1. The nearly vertical line which shows the deviation from verticality on a common scale from 0° to 9°.
2. A dashed line which runs diagonally or rotates as the tool is drawn up in the circular portions of the hole. This line ceases to rotate on encountering an elliptical zone and gives the relative bearing of the tool on a scale of 0 to 360 degrees with respect to azimuth of No.1 elctrode. From this the bearing of the hole drift can be calculated.

The tool normally rotates as it is drawn up the well and in many depth ranges the calipers will indicate essentially equal diameters equal to the drill-bit diameter. This can be seen in the bottom and top sections of figure 3. It is observed, however, in other depth ranges that the tool ceases to rotate and the calipers indicate different diameters. This is the result of extensive fracturing

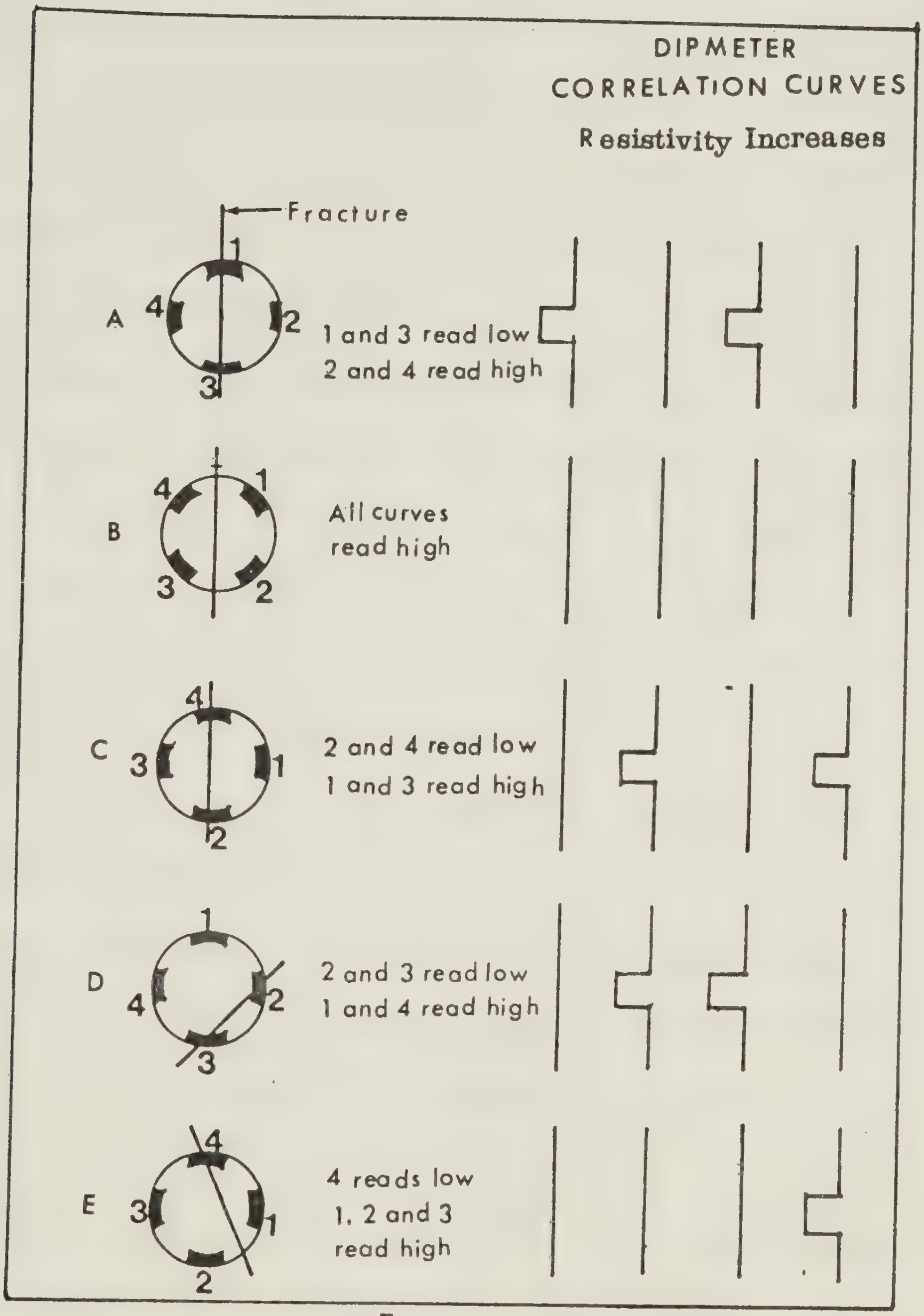


Figure 4.... Responses of HDT correlation curves to vertical fractures. (schematic)

causing the borehole to spall and wash out on opposite sides,thus becoming elliptical. Usually the smaller diameter is equal to the drill bit. This condition has been named by Babcock (1978) a **BREAKOUT**, and is illustrated in figure 5 D. Other situations encountered in a borehole are also shown in figures 5 A to C. In Figure 5 D one pair of calipers has become trapped in a locally elongated section of the hole. The orientation of the breakout can be estimated from the azimuth of the trapped caliper pads. In Figure 3, a breakout is shown between depths 9418 and 9527 feet. Calipers 2 and 4 (solid diameter line) indicate the greater diameter and the stationary azimuth trace shows No.1 electrode near 200°. The azimuth of the long axis of this breakout is near 200-90=110° relative to the magnetic north. The final orientation is 110° plus the magnetic declination.

The success of the HDT in determining sedimentary bedding planes has led to an extensive use of this tool in many areas, starting from the West Texas Ellenberger play in 1969, the cretaceous of North Louisiana and Mississippi and also in the limestone of the Mooringsport of the Waveland field of Mississippi.

During the interpretation of Schlumberger 4-arm dipmeter logs wells in Alberta, Cox (1970) observed that through the Wapiabi shale (a predominantly dark gray shale of both Colorado and post Colorado age in the upper cretaceous period) interval of the Strachen-Ricinus area (see Fig. 16 shaded portion) of West Central Alberta

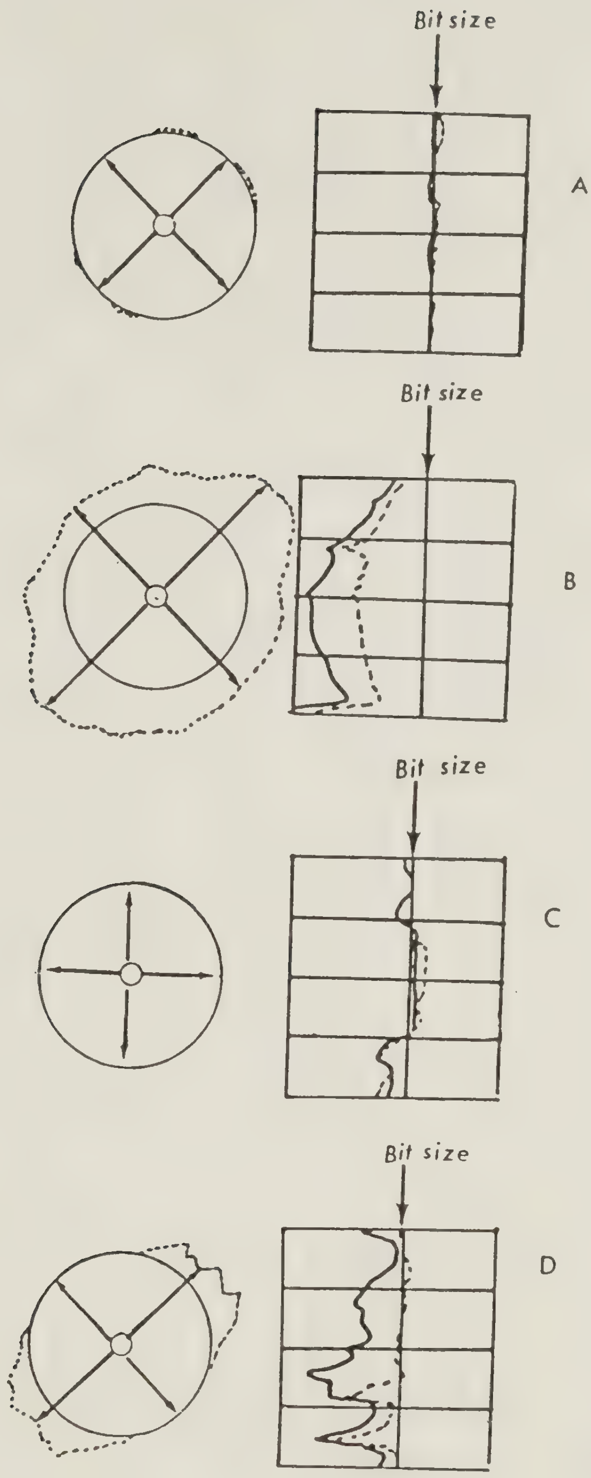


Figure 5.... Dual-caliper response to possible conditions of borehole shape.

adjacent to the Rocky Mountain foothills, where the borehole was not at bit size it was always elongated in the northwest-southeast direction. Structural dips were usually northeast or southwest. Nevertheless, several wells in this area in which structural dips were differently oriented showed the same northwest-southeast elongation. This observation led Cox to make a broader statistical study of 4-arm dipmeter logs in 31 zones from 17 wells scattered about Alberta and the North West Territories.

This new study ranged from Cretaceous shales to Devonian carbonates, in which dip values ranged from 0° to 30°. The orientation of the long axes of the holes had an average direction of N47°W to S47°E. A few elongations formed another group perpendicular to this major trend (Fig. 6 A). That the dip direction is not a controlling factor for the hole elongation is shown in figure 6 B.

An interesting feature of these elongations observed by Cox (1970) was that they were confined to discrete depth intervals within a hole and separated by uncaved beds. This observation led Babcock (1978) to suggest that the elongation might be caused by the drill encountering zones of steeply dipping fractures. Babcock later undertook a study of the phenomenon of hole elongation using the caliper portion of the 4-arm dipmeter logs, and extending his investigation to 23 wells in various sedimentary rocks widely distributed through Alberta.

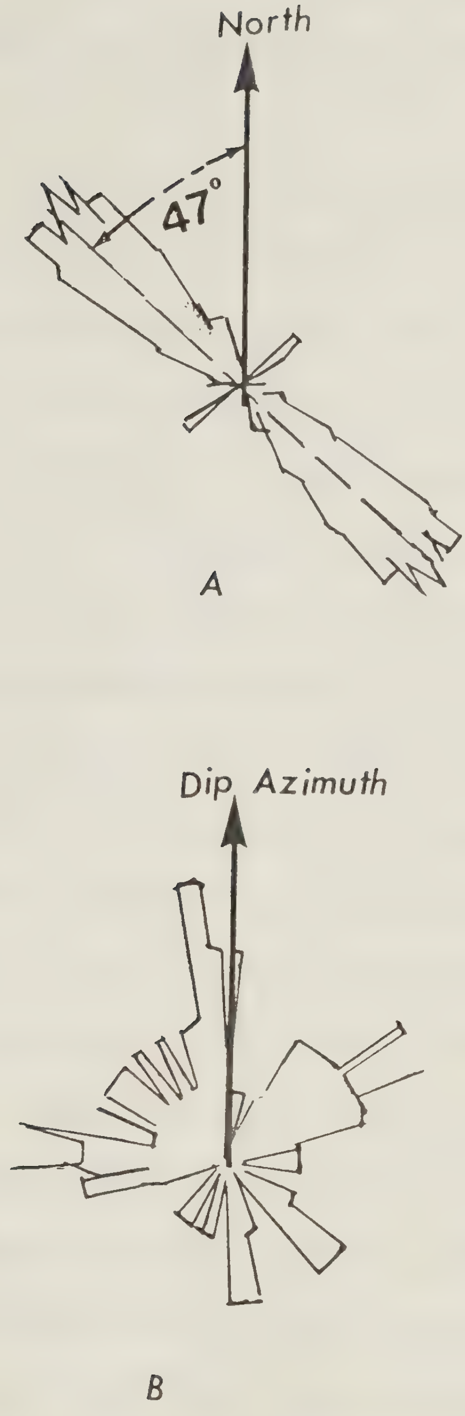


Figure 6.... Orientation of breakout long axis with respect to (A) North and (B) Dip azimuth. (J. Cox, 1970)

He noted the following properties of breakouts

1. The breakout zones may be short discrete events, or may persist over depth intervals of several tens or hundreds of feet.
2. A breakout of 2 to 4 feet commonly slows down the tool rotation or may have no noticeable effect on rotation; whereas a longer breakout is commonly associated with a cessation in the rotation of the tool.

To explain his observations, which were consistent with Cox's (1970) observations, Babcock turned to his study of the regional jointing in exposed bedrock of the Alberta plains and in the Fort McMurray area of northeast Alberta (Babcock, 1973,1974,1975). Within this area two orthogonal joint systems made up of vertically dipping extensional fractures are present. System 1 has sets striking northeast and northwest roughly normal to and parallel with the Rocky Mountain Belt. The northeast striking set is dominant in the sense that it is most commonly developed in that joints of this set usually cut across joints of other sets, which terminate against them. A second joint system (System 2, Babcock, 1973) having sets striking roughly North-South and East-West was also observed. This system was common in the Fort McMurray area and in the southernmost part of Alberta and occurred elsewhere in the province. These two joint systems were reported (Babcock, 1973) in nearly flat-lying sedimentary rocks ranging from late Devonian to Paleocene in age, in outcrops of shales, siltstone, sandstone, limestone

dolomite and coal distributed through many thousands of square kilometers and several thousands of meters of the stratigraphic column. Out of a total of 1,236 nearly vertically dipping joints measured, Babcock observed that although joint sets were well defined at most stations, set directions between stations varied considerably. Nevertheless, the sets striking northeast and northwest were most developed.

Regions covered by Babcock in his study of breakouts included the Claresholm district. Here he compared the joint azimuths measured at 10 outcrops and the azimuths of elongations from five wells. The mean directions of the elongations he observed showed a variation in strike ranging from 129° to 155.5°, thus corresponding closely to the northwest-southeast striking joint set. However, the elongations showed much less variability than do the strikes of individual joints of the northwest striking set in the area. A comparison of all azimuths of elongation (41 in all) with that of all joint strikes (1,236) in the area is shown in Figure 7. Clearly there is no close correspondence as a result of the predominance of one joint set striking at approximately 175° (North-South), which falls under Babcock's System 2.

Similar comparisons were made by Babcock in his Red Deer study between 400 azimuths of joints in bedrocks and 67 breakout elongations in nearby oil wells. Here, however, joint sets belong to the System 1 and the dominant direction

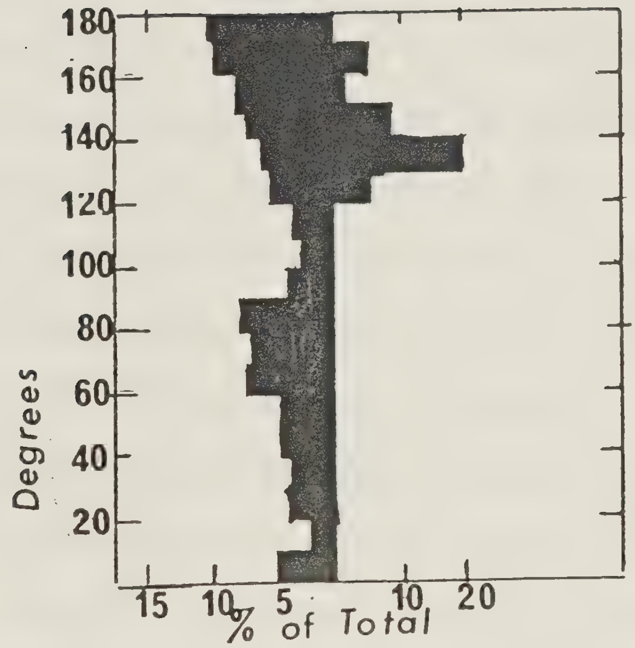


Figure 7.... Histogram comparing (left) strikes of 1,236 joints measured at 10 outcrops in Claresholm region, southwest Alberta, with (right) azimuths of 41 elongated breakouts from five wells. (Babcock, 1978)

of hole elongation was northwest-southeast at about 140 °.

Babcock's study of 23 wells scattered throughout Alberta led him to draw the following conclusions,some of which had been made by Cox (1970):

1. In most of the 23 wells studied, the breakouts are in the northwesterly direction. However, in some wells a small number of breakouts may follow a northeast trend.
2. The azimuths of elongation are parallel to well developed sets of regional joints which are present wherever joint directions have been studied.
3. Hole deviations from verticality, changes in the magnitudes and directions of bedding dips, and lithology are unrelated to breakouts.
4. The preferred orientation of breakouts could not be the result of the drill encountering vugs because this would lead to hole elongations with no preferred orientation.
5. Babcock further stated that through his informal discussion with engineers involved with hydraulic fracturing and from consideration of the tectonic setting, the inferred direction of intermediate stress in rocks of the Alberta plains is normal to the trend of the Rocky Mountain Belt or roughly Northeast Southwest and the maximum stress is vertical, with the minimum stress direction inferred to be Northwest Southeast parallel with the dominant azimuth of hole elongation.

From these general conclusions Babcock finally concluded that the breakouts occur as a result of the drill

encountering steeply dipping fractures or zones of steeply dipping fractures, which may or may not be open. The oversize holes in carbonate rocks he related to solution-widened joints.

Bell and Gough (1979) found Babcock's hypothesis for the cause of breakouts very difficult to accept. Their most serious objection was the fact that the azimuthal distribution of breakouts is very unlike that of joint sets at the surface. They argued that given four concentrations of joint directions on the surface (Babcock 1973) NW, NE, N, and E, they would expect concentrations of breakout azimuths in all the four directions on Babcock's hypothesis, rather than only one significant concentration of subsurface breakout direction (NW).

Secondly, Bell and Gough wondered if such surface joint directions would necessarily be parallel to those at depths extending beyond 2 km at which breakouts have been observed. In this connection they remarked that sediments involved in the study in the Alberta Plains were laid down in varying tectonic settings between Devonian and Cretaceous times; and furthermore joints may arise in several ways after deposition of sedimentary rocks.

In an attempt to find an interpretation that would account for both the breakouts in the wells and the surface joints System 1 of Babcock, Bell and Gough (1979) proposed that both features result from a general stress field acting throughout the Alberta Plains and oriented with the larger

principal horizontal stress NE-SW and the smaller of the two horizontal stresses parallel to the Rocky Mountain fold axes. Using the Kirsch equations for the stress near a circular hole, in a medium under biaxial stress, they argued that with large enough, unequal horizontal stresses oriented as above, the holes themselves could concentrate the stresses so as to produce subsurface breakouts with long axes in the NW-SE direction. Such concentrations of stress are believed to arise at the time of drilling.

If the breakouts in Alberta are shear fractures caused by the concentration of stress at the walls of the borehole as proposed by Bell and Gough (1979), the larger horizontal compression is orthogonal to the azimuth of the breakouts and hence nearly Northeast-Southwest in Alberta. Their hypothesis provides no indication of the magnitudes of the principal stresses other than the fact that the horizontal principal stresses are large and unequal. Gough and Bell (1982) have recently made a quantitative study of shear fracturing near a borehole, and have shown that such fractures can form breakouts with the observed properties.

Stress measurements in mines in several continents reveal that the vertical principal stress approximates (within 20% or less in most cases) the overburden pressure (McGarr and Gay, 1978). Furthermore, the proximity of the thrust faults of the Rockies to areas covered in the studies by Cox (1970) and Babcock (1978) coupled with the fact that the Rockies are fold mountains led Bell and Gough (1979) to

suggest that a situation with S_1 (the maximum principal stress) vertical (a normal-fault stress field) is most unlikely in Alberta.

This fact is further strengthened by the occurence of breakouts at depths of 500 meters or less. Laboratory experiments by Gay (1973) indicate that the threshold pressure for spalling in a circular hole under equal orthogonal pressures is about 100 MPa. With unequal pressures, however, spalling would be expected with the larger compression around 30 MPa. But at a depth of 500 m the overburden pressure will be about 12 MPa. If S_1 is vertical then both S_2 and S_3, which are horizontal, will be smaller than this value (12 MPa) and may be too small to produce shear fractures. This now leaves us with either a thrust fault or a strike-slip (wrench) fault stress field. Bell and Gough's hypothesis fits either of these two stress fields and the breakouts are consistent with either case.It is worth noting that the breakouts alone cannot reveal which of the two stress situations prevails in Alberta.

In a later paper, Gough and Bell (1981) added additional wells in Alberta to their study of breakouts.They also extended the area covered into northeastern British Columbia. In addition results from hydraulic fracturing in an oil field in West-Central Alberta were discussed. They suggested that some local anomalies in breakout orientations might represent local variations in the stress field.

Lo and Morton (1976) attributed failures of tunnel roofs in Ontario to interaction of the tunnel with large horizontal compressive stresses transverse to the tunnel. Dusseault (1977) suggested that unequal horizontal compressive stresses prevail in several areas in Alberta, to account for the propagation of vertical fractures during hydraulic fracturing in Northeast-Southwest vertical planes. Such fractures imply a horizontal least principal stress (S_3)directed Northwest-Southeast. The formation of tensile fractures normal to S_3 during hydraulic fracturing was first proposed by Hubbert and Willis (1957). This leads to the expectation that in a thrust stress field (S_3 vertical) hydraulically formed fractures will be horizontal (Kehle, 1964). This is difficult to verify in many cases, because horizontal fractures are hard to detect. Zoback et al (1977) argue that the inflatable packers inhibit such horizontal fractures, and that horizontal fractures form only if fluid penetrates pre-existing planes of weakness. This contention is supported by laboratory experiments by Haimson and Fairhurst (1970). Haimson (1976b) suggested that if $S_V = S_3$ then the induced fractures initiate in a vertical plane and then become horizontal as they propagate based on the fact that energy propagates along the path of least resistance. This can be observed in the pressure-time history where the asymptotic shut-in pressure is smaller than the instantaneous shut-in pressure. In such a situation the instantaneous shut-in pressure is not equal to the least

principal stress but rather the smaller horizontal principal stress with the asymptotic shut-in pressure being equal to the least principal stress S_3.

In the J Lease of the Pembina Oilfield, Macleod (1977) noted during secondary oil recovery from Cardium Formation sandstone that permeability was greatest in the Northeast-Southwest direction. This observation implied either a fracture system or else a permeability trend oriented Northeast-Southwest. But Neilson (1957) showed the isopach axes in this formation and area to be trending Northwest-Southeast. Thus one would expect a permeability trend related to the process of deposition to run NW-SE. Gough and Bell (1981) therefore concluded that Macleod's observation could be better explained in terms of vertical fractures oriented NE-SW, which would imply a NW-SE orientation of S_3. Six wells logged with the HDT in this area were identified and studied by Gough and Bell. The breakouts occur in rocks of Paleozoic ages over depths from 2500 to 4500 meters. Azimuths of hole elongation were tightly grouped with mean values ranging between 132° and and 141°, with variations over approximately 20° in individual wells.

Imperial Oil in 1978 published information on their Cold Lake projects in far eastern Alberta. Induced vertical fracture orientations varied from N 30° E to N 45° E implying that the minimum principal stress was horizontal in this region and oriented between 120° and 135°. The larger

horizontal stress would then lie between 30° and 45°. Imperial Oil ran no HDT logs in wells in the Cold Lake region (J.S.Bell, personal communication with the Company). However, Gough and Bell (1981) located one well in this region logged by the HDT. The azimuth of a single breakout, at depth 477 to 479 m in the Clearwater Formation, was 131° suggesting the major horizontal stress direction of 41°. Recently, Gough and Bell (1982) have reported comparisons of breakout azimuths in Colorado, in East Texas and in northwestern Canada with other indications of stress orientations in those regions. In every case the observations support their explanation of breakouts as a consequence of stress concentration by the borehole in an anisotropic stress field. The hydraulically induced fractures at West Pembina and at Cold Lake indicate a strike-slip type stress field (S_1 and S_3 horizontal, S_2 vertical) is most likely present in most parts of Alberta.

This thesis reports a study of the statistics of the azimuthal distribution of breakouts in oil-wells in Alberta in relation to depth, lithology, formation and age of rocks, together with the geophysical implications of breakouts.

II. STRESS AND FRACTURE IN THE EARTH'S CRUST

STRESS

If one considers a simple prism of cross-sectional area a subjected to a force **F**,as shown in Fig. 8, the stress S_z acting on the end surface ABCD is given by

$S_z = F/a$ --2-1

It can be seen that the force **F** has no component acting parallel to the ABCD surface. This means it exerts no shear stress on this surface. By definition, any stress acting perpendicular to a surface along which the shear stress is zero is a principal stress. Thus in this case S_z is a principal stress. Here, the suffix indicates the direction in which the stress acts. Other principal stresses may be orientated parallel to the X- and Y- axes, and would be designated S_x and S_y respectively. If the relative intensities of the principal stresses are known, they may be termed the maximum (or greatest), intermediate and minimum (or least) principal stresses (i.e. S_1, S_2, S_3 respectively).

If one considers the action of the force **F** on a surface GHIJ inclined at an angle Ø as shown in the Figure 8, the component of **F** acting normal to GHIJ is given by,

$F_n = F.\sin Ø.$

However, it will be seen that the area a'of GHIJ is greater than the area a of ABCD, and that

$a' = a/\sin Ø$.

Therefore, the normal stress S_n acting on the inclined

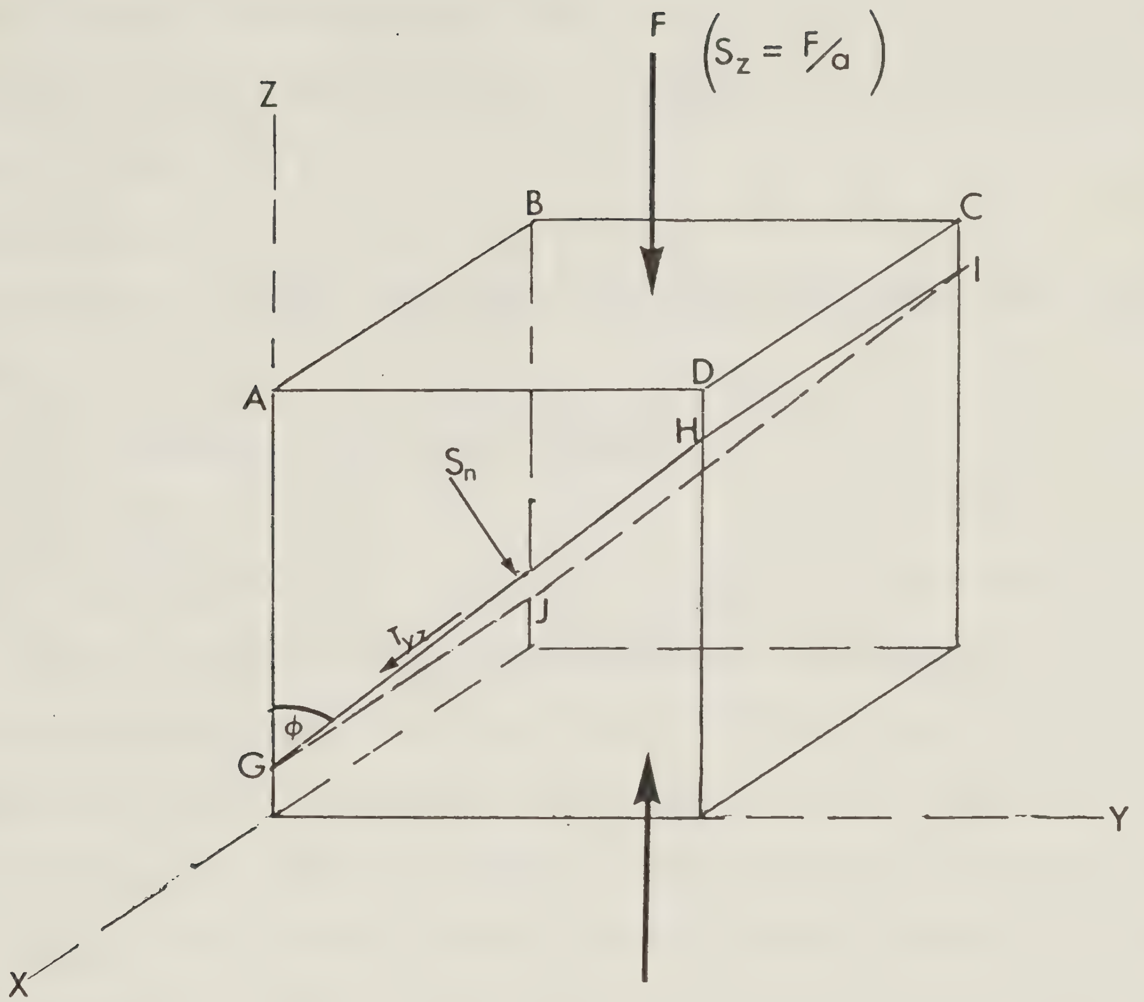


Figure 8.... Normal and Shear stresses acting on external and internal surfaces of a unit cube subjected to a force F

surface is

$F_n/a' = F.\sin Ø/a' = (F/a).\sin^2 Ø$

so that

$S_n = S_z.\sin^2 Ø$ ---------------------------------------2-2

Similarly the component of F tangential to the inclined plane is given by

$F_t = F.\cos Ø.$

Consequently the shear stress (T) acting along the plane equals

$F_t/a' = F.\cos Ø/a' = (F/a).\cos Ø.\sin Ø$

that is

$T = S_z.\cos Ø.\sin Ø$---------------------------------------2-3

Shear stresses as well as other stresses may be related to co-ordinate axes. We denote by T_{zy} the shear stress on yz-planes acting parallel to the y-axis. Similarly T_{zx} denotes a shear stress acting in the zx-planes parallel to the x-axis. The stress across a plane whose normal is in the y-direction will have components T_{yx}, S_y, T_{yz} and that across a plane whose normal is in the x-direction will have components S_x, T_{xy}, T_{xz}. The nine quantities below

$$\begin{matrix} S_x & T_{xy} & T_{xz} \\ T_{yx} & S_y & T_{yz} \\ T_{zx} & T_{zy} & S_z \end{matrix} \quad \text{---------------------------------------2-4}$$

are called the stress components and give a complete specification of the stress at a point. It can be shown that $T_{yx} = T_{xy}$, $T_{yz} = T_{zy}$ and $T_{zx} = T_{xz}$, so that only six quantities out of the nine are needed to specify the stress at a point.

The stress components in Eqn.(2-4) are in fact the components of a mathematical entity called a tensor,(and tensor analysis is much used in developing the higher parts of the theory of elasticity where x,y,z, are replaced by 1,2,3, respectively). A tensor in which $T_{xy} = T_{yx}$, $T_{yz} = T_{zy}$, $T_{xz} = T_{zx}$ is said to be symmetric.

In a biaxial stress field it can be inferred from Eqn. (2-2) and Eqn. (2-3) that the stresses acting normally and tangentially to a plane inclined at Ø to S_1 and hence (90+Ø) to S_3 will be represented (on superposition) by

$S_n = S_1.\sin^2\text{Ø}+S_3.\cos^2\text{Ø}$

and

$T = (S_1-S_3).\sin\text{Ø}.\cos\text{Ø}$ ---------------------------------2-5

which can be written in terms of the double angle 2Ø as

$S_n = (S_1+S_3)/2 - ((S_1-S_3).\cos 2\text{Ø})/2$ and

$T = ((S_1-S_3).\sin 2\text{Ø})/2$ ---------------------------------2-6

Equation 2-6 may be represented graphically by means of Mohr's stress circle, which will be discussed later in this chapter.

Subsurface rocks are normally in a state of compressive stress except very near the surface because of the weight of overlying rocks. This overburden weight creates stresses in both the vertical and horizontal directions. The stress field at a point can be represented by S_1, S_2, S_3 as already defined. Over long periods of geologic time the earth has exhibited an appreciable degree of mobility during which rocks have been repeatedly stressed to the limit of failure

to produce faulting and folding. The problem of rock squeeze (i.e. continuous deformation of the rock) has been recognised in parts of the crust. In Southern Ontario structures built in rocks have exhibited distress in various degrees during or subsequent to construction (Lo, 1978). Geological processes such as faulting,folding, and pop-ups or buckling of the surface rock strata, without any apparent change of external loading, may be interpreted as evidence of existence of high horizontal stresses. In a study of geological features and movements of structures in rock in New York State, Rose (1951) associated the rock squeeze with the possible existence of high horizontal in-situ stress in the rock formations. Such phenomena require that substantial differences must exist between the principal stresses. Sbar and Sykes (1973) have used information from postglacial geologic features such as east-west rock squeeze in western New York and Niagara, and bridge abutments moving together to infer that the maximum compressive stress in this area has an easterly trend. Postglacial buckles or pop-ups near Chippewa Bay, New York have also been ascribed by Sbar and Sykes as not due to any environmental factors other than large horizontal compressive stresses. Pop-ups have also been encountered elsewhere in western New York where the lithostatic load has been reduced by quarrying (Sbar and Sykes personal commun. with J. Davies, 1972). Deformation indicative of a high horizontal compressive stress was also observed in various parts of Ontario (Coates, 1964), where a

pop-up about two and one half meters high, striking northwest, occurred overnight in a quarry after it had been excavated to a depth of 15 meters. Finally the results obtained from geologic features, in-situ stress measurements and earthquake distributions in eastern and central North America may be related to the presence of high stress.

The orientation of the trajectories of the principal stresses in space is largely determined by the condition which they must satisfy at the earth's surface. This is a free surface, on which normal and shear stresses vanish. Since the only planes on which the shear stresses are zero are those perpendicular to the principal stresses, it follows that one of the three trajectories of principal stress must end perpendicular to the surface of the ground, and the other two must be parallel to this surface. Therefore, in regions of gentle topography with simple geologic structures the principal stresses should be nearly horizontal and vertical, with the vertical stress approximately equal to the pressure of overlying material. Measurements of stress in mines in several continents show that in many cases the vertical normal stress is, within about 20%, equal to the overburden pressure $S_v = \rho . g . h$, where ρ is the density of the material, g is gravity and h is the depth. If the lateral stress were due solely to elastic response of the rock S_v, the horizontal principal stresses would be $S = s = \nu/(1-\nu) . S_v = S_v/3$ where ν is Poisson's ratio. Such a stress field would produce normal

faults at any depth at which the stress difference exceeded the strength of the rock. However, observations in underground structures, quarries and hydraulic fracturing in boreholes indicate that the horizontal stresses S and s S>s are not generally equal and do not vanish close to the surface, a necessary consequence if the horizontal stresses were due simply to elastic response of the rock to overburden pressure.

Measurements in several continents of in-situ stress in rocks show that in many cases the horizontal stresses are much higher than the vertical stress calculated from the overlying weight of the rock (McGarr and Gay, 1978 ; Hast, 1973; Herget, 1974). Frequently the horizontal stresses S and s increase linearly with depth. It is thus evident that large and unequal horizontal principal stresses are widespread in the continental crust of the earth.

Relationships Between Principal Stresses at Failure

Most substances behave elastically at low stresses. As the stress is increased the body will begin to yield at some point if it is ductile, while if the body is brittle it will fracture at some point without appreciable yielding. The term fracture implies the appearance of distinct surfaces of separation in the body and yield is used for the onset of plastic deformation. Flow is used for unrestricted plastic deformation. Both flow and fracture (also known as failure) are observed on large and small scales in geologic material so that the criteria for them are vital for the

interpretation of geologic phenomena.

For brittle materials in tension, *tensile or cleavage* fracture takes place across a surface perpendicular to the direction of tension (Fig. 9 A). For brittle materials in compression, shear fracture takes place along a pair of planes or a cone approximately in the direction of the greatest shear stress but always between this direction and the direction of the largest compressive stress (Fig. 9 B). The maximum shear stress theory, which dates back to Coulomb (1773), states that failure occurs at a point when the maximum shear stress is equal to the shear strength of the material. If $S_1 \geq S_2 \geq S_3$ are the principal stresses at a point, taking compressive stress positive, the maximum shear stress has magnitude $(S_1-S_3)/2$, and occurs across a plane containing the direction of S_2 and whose normal bisects the angle between the greatest and least principal stresses. The theory implies that if C_0 is the compressive strength of the material in an unconfined compression test in which $S_3=S_2=0$, $S_1=C_0$, the material will fail across any plane inclined at 45° to the direction of compression for a frictionless material. For real materials the angle is less than 45°. The theory also implies that the tensile and compressive strengths are equal. The theory has been modified by Navier to fit qualitatively most of the observed facts, and is used by Anderson in a discussion of the types of geological faulting. In this modification, instead of assuming that fracture takes place across the plane over which the shear

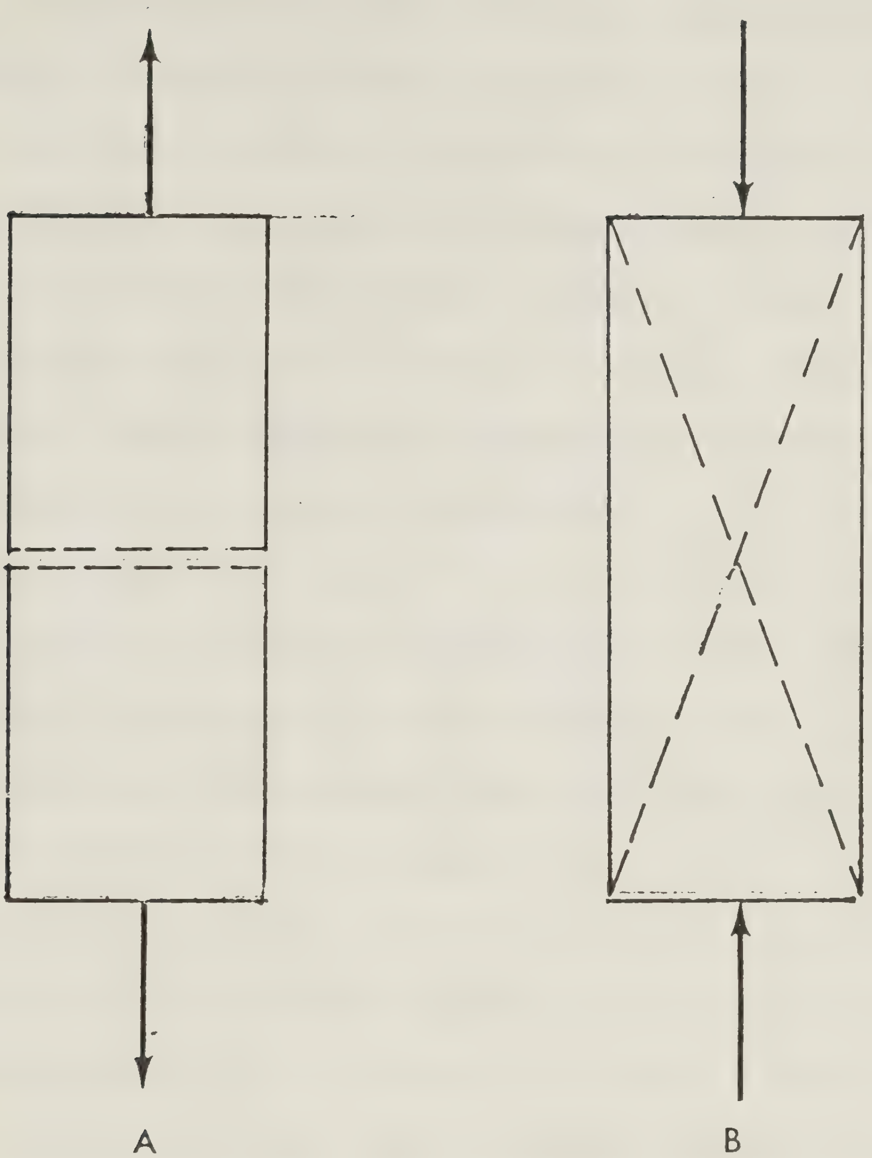


Figure 9.... Failure of a brittle material.(A) Tensile fracture and (B) Shear fracture

stress first becomes equal to the shear strength S_0 of the medium, it assumes that this shear strength is increased by a constant u times the normal pressure across the plane. Because of the analogy to ordinary friction in which the tangential force is u times the normal reaction, u is known as the coefficient of internal friction. Thus, if S_n and T are the normal and shear stresses across a plane, fracture takes place on the plane at which the magnitude of T first becomes equal to $S_0 + u.S_n$. Therefore,

$$| T | = S_0 + u.S_n \text{ ------------------------------ } 2\text{-}7$$

This is the Navier-Coulomb criterion for shear failure. Let us discuss the case of two dimensions first. If S_1, and S_2 are the principal stresses,we can then write Eqn. (2-6) as

$$S_n = (S_1+S_2)/2 + (S_1-S_2)\cos 2\emptyset/2$$

$$T = (S_1-S_2).\sin 2\emptyset/2 \text{ ------------------------------ } 2\text{-}8$$

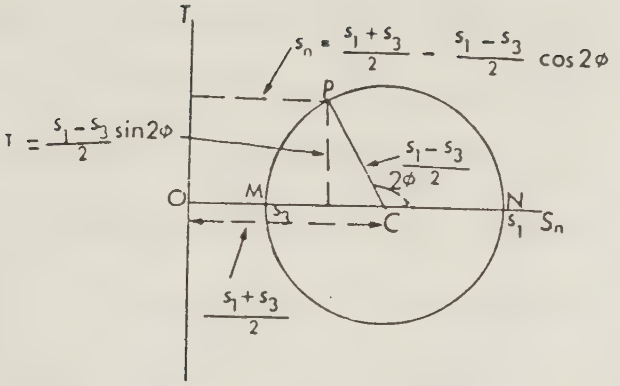
Only values of $\emptyset$ between 0 and 90° need be considered, since only the magnitude of T occurs in Eqn. (2-7), so that changing the sign of $\emptyset$ only changes the sign of $\sin 2\emptyset$ and does not affect the magnitude of S_n or T. The shear stress at failure is thus symmetrical about $\emptyset=0$. It can be shown that failure takes place across a plane whose normal makes $\emptyset$ with S_1 where $\tan 2\emptyset = 1/u$. If u=0, then $\emptyset=45°$; if u=1, $2\emptyset=135°$ and $\emptyset=67.5°$; if u---> infinity, $\emptyset$-->90 that is as u increases the plane of fracture moves towards the direction of maximum stress. Values of u of the order of 1 are inferred from the directions of fracture of rocks in testing machines, and also from geological faulting (Jaeger,1956;

Price,1973). It should be remembered that,because of the symmetry in $\emptyset$ mentioned earlier, the theory leads to two possible planes of fracture equally inclined to the principal stresses and gives no reason for preferring either. For failure under combined stress in terms of the compressive and tensile strengths, C_0 and T_0 of the material,the relation

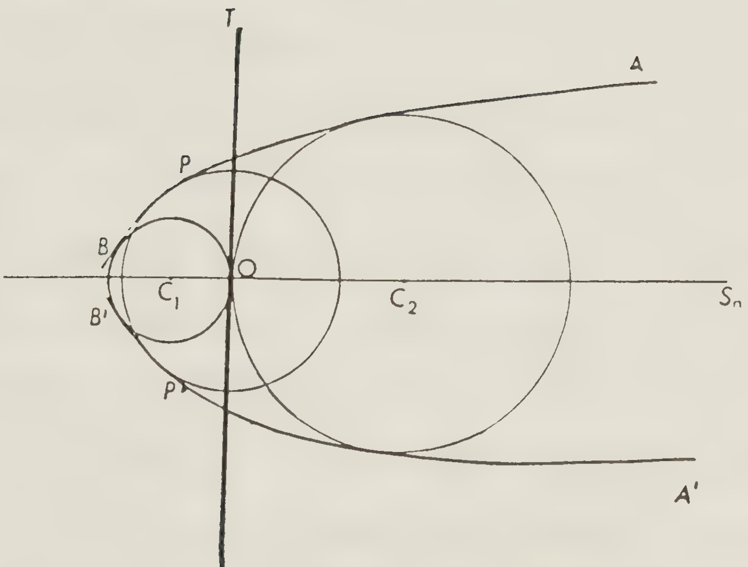
$$C_0/T_0 = (\sqrt{(u^2+1)} + u)/(\sqrt{(u^2+1)} - u)$$

holds. The theory predicts that the compressive strength of a material is always greater than its tensile strength but the ratio is rather smaller than that found in practice. The theory also predicts that under any conditions the normal to the plane of fracture makes the same angle arctan(1/u)/2, with the direction of greatest principal stress. Although this is approximately true for compressive stresses, it is very far from the truth in the case of pure tension when the failure is usually by brittle fracture with the plane of fracture normal to the direction of tension. The reason may be that T_0 should not be the actual tensile strength but the value at which shear failure in tension would take place if tensile fracture did not occur in practice before this value is reached. Nevertheless, the theory gives a reasonably accurate account of the behaviour of rocks under combined compressive stresses.

Mohr's representation of stress and failure is useful (Fig. 10). Mohr's theory assumes that at failure across a plane the normal and shear stresses across the plane, S_n and



a



b

Figure 10.... Representation of stresses on any plane in a two-dimensional stress system by means of Mohr's stress circle.

T, are connected by some relation $T = f(S_n)$. This relation may be plotted on a (S_n, T) plane and since changing the sign of T simply changes the direction of failure but not the condition for it,the curve is symmetrical about the S_n-axis. Any state of stress can be represented by a Mohr circle on the (S_n, T) plane. In representing the normal and shear stress across a plane in a biaxial stress field on the Mohr's Stress circle, the normal stress S_n and shear stress (T) are chosen as co-ordinate axes. Here the greatest principal stress S_1 and the least principal stress S_3 are represented by ON and OM respectively on the S_n-axis. The quantity $(S_1+S_3)/2$ of Eqn. (2-6) represents the mid-point C on the S_n axis between M and N, while $(S_1-S_3)/2$ represents half the distance between M and N. If a circle is drawn with centre C and radius $(S_1-S_3)/2$, then for any specific values of S_1 and S_3 ,this circle represents the conditions of Equation 2-6 where $2\emptyset$ is measured as indicated in Fig. 10 a. This construction as we shall see is used in representing the values of shear and normal stresses at failure. If this circle lies wholly within the failure envelope ABA'B' in Fig. 10 b, the stresses involved nowhere attain the critical values. If any portion lies outside it the material could not withstand the stresses. Obviously, the limiting case is that of a circle such as those of centres C_1, O and C_2 which just touch the curves AB and A'B'. In this case failure will take place under stress conditions corresponding to the points PP', that is, over planes whose normals are inclined

at angles of half the angle PCN (Fig. 10a) to the direction of the greatest principal stress. The curve AB will be the envelope of all the circles corresponding to all conditions at which fracture takes place and for this reason is known as the *Mohr envelope.*

In principle, three circles which touch the envelope can be found from simple experiments. These are those of centres C_1, O and C_2 (Fig. 10 b) , corresponding to tension, simple shear, and compression. But in practice it is difficult to perform shear or tensile tests on rock materials. An approximation to the Mohr envelope for many rocks, from results of triaxial tests, is the pair of straight lines

$$|T| = T_0 + u.S_n$$

corresponding to the Coulomb-Navier criterion for fracture under shear stress, where T_0 is the shear strength. In this case the normal to the plane of fracture makes an angle (in the second quadrant) arctan(1/u)/2 with the direction of the greatest principal stress. When applied to triaxial stress, the Mohr theory leads to the result that only the Mohr circles for the plane containing the greatest and least principal stresses need be considered and that fracture always takes place in planes containing the direction of the intermediate principal stress. This is not altogether consistent with the experimental results.

One important application of these results is the study of faults which are fractures of the rocks of the earth's

crust (Fig. 11). Geologists distinguish three major types of faults and Anderson (1951) has shown that these are determined by the relative magnitudes of the principal stresses. One principal stress will always be vertical, and three cases arise according as this is the greatest, intermediate, or least principal stress. In the case where the vertical principal stress is the least in magnitude and the other two principal stresses are compressive (Fig. 11 A), the fault is known as a *thrust* fault. The planes of fracture pass through the direction of the intermediate principal stress and makes angles of less than 45° with the direction of the greatest compressive stress which is horizontal, (Fig. 11 B). This applies in regions of active tectonic compression or erosion or vertical unloading. When the intermediate principal stress is vertical, we have Figure 11 C. The failure can take place on either of two vertical planes (Fig. 11 D), which are equally inclined at angles of less than 45° to the direction of the greatest compressive stress. This type of fault is called a *transcurrent, wrench or strike-slip fault.* When the vertical principal stress is greatest as may often be the case at considerable depths, and in rift structures near the surface, the type of failure is called *normal faulting.* Here the faults make angles less than 45° with the vertical (Fig. 11 E).

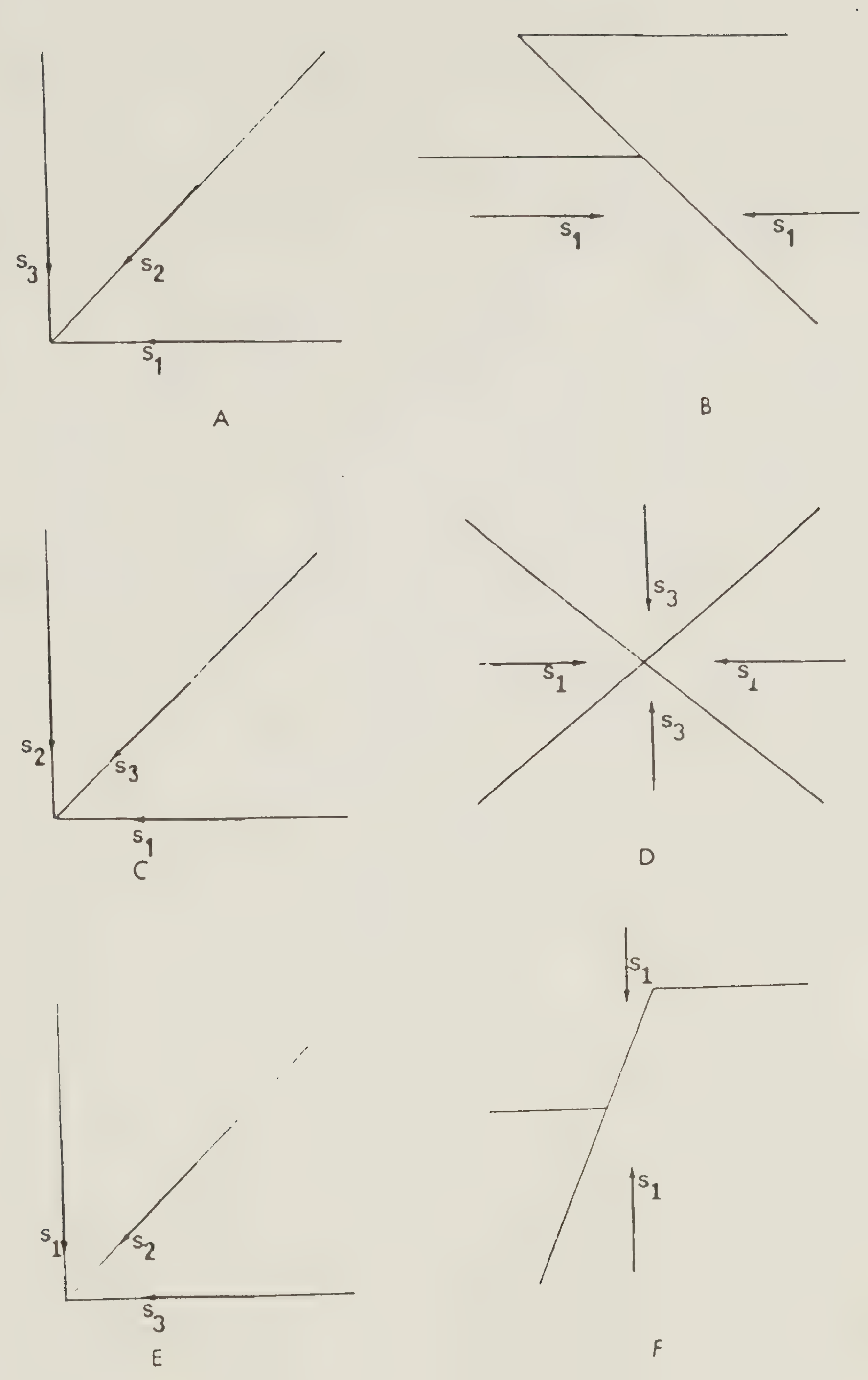


Figure 11.... Types of faulting in relation to the principal stresses; A and B, Thrust fault, C and D, Wrench fault, E and F, Normal fault.

Stress Concentration Caused by the Borehole

The presence of a borehole distorts the pre-existing stress field, because as discontinuities in the earth's crust, boreholes cause redistribution of stresses in the nearby rock. An approximate calculation of this distortion is made by assuming that the rock is elastic, the borehole smooth and cylindrical and the borehole axis vertical and parallel to one of the regional principal stresses. Kirsch (1898) found an analytic solution of the problem of the stress field near a small hole of radius a in a large plate under uniaxial compression S. The solution as given by Timoshenko and Goodier (1951) is given below.

Let Figure 12 represent a plate subjected to a uniform compression of magnitude S in the x-direction. If a small circular hole is made in the middle of the plate, the stress distribution in the immediate vicinity of the hole will be changed. However, by Saint-Venant's principle we know that the change will be negligible at distances which are large compared with a, the radius of the hole. Let us consider the portion of the plate within a concentric circle of radius b, large in comparison with a. The stresses at the radius b are effectively the same as in the plate without the hole and are therefore given from Equations (2-2) and (2-3) by

$(S_r)_{r=b} = S.\cos^2\emptyset = S/2.(1+\cos 2\emptyset)$

$(T_{r\phi})_{r=b} = -1/2\ S.\sin 2\emptyset$ ------------------------------------ 2-9

For stresses disposed symmetrically about a point of weakness in the earth's crust the direction of the principal

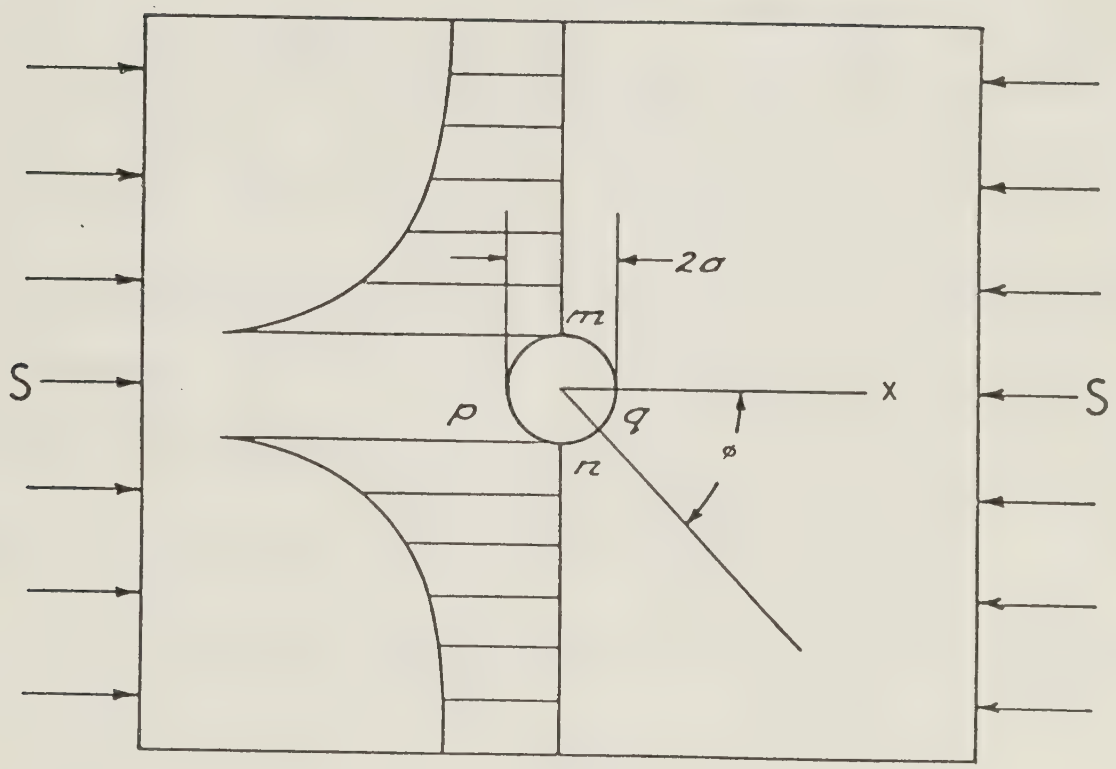


Figure 12.... A plate submitted to a uniform compression of magnitude S in the X-direction with a small hole in it

stresses will be vertical, radial, and tangential. The forces acting around the outside of the ring in Equation 2-9, having the inner and outer radii r=a and r=b give a stress distribution within the ring which can be considered as consisting of two parts. (a) The first is due to the constant 1/2 S of the normal forces. (b) The remaining part consists of the normal forces 1/2 S.cos2Ø together with the shearing forces -1/2 S.sin2Ø. The stresses produced by this second part may be derived from a stress function of the form

$$\Phi = f(r).\cos 2\varnothing \text{--} 2\text{-}10$$

This stress function can be substituted into the compatibility equation

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2}\right)\left(\frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r}\frac{\partial \Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \phi^2}\right) = 0$$

to yield an ordinary differential equation from which f(r) can be determined.

$$(d^2/dr^2+d/rdr-4/r^2)(d^2f/dr^2+ df/rdr-4f/r^2)=0$$

The general solution is

$$f(r) = A.r^2 + B.r^4 + C/r^2 + D$$

Equation 2-10 then becomes

$$\Phi=(A.r^2+B.r^4+C/r^2+D).\cos 2\varnothing \text{--------------------------------} 2\text{-}11$$

The stress components are;

$$S_r = \frac{1}{r}\frac{\partial \Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \phi} = -\left(2A + 6\frac{C}{r^4} + 4\frac{D}{r^2}\right)\text{COSINE } 2\phi$$

$$S_\phi = \frac{\partial^2 \Phi}{\partial r^2} = \left(2A + 12Br^2 + 6\frac{C}{r^4}\right)\text{COSINE } 2\phi \qquad \text{---------------} 2\text{-}12$$

$$T_{r\phi} = -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Phi}{\partial \phi}\right) = \left(2A + 6Br^2 - 6\frac{C}{r^4} - 2\frac{D}{r^2}\right)\text{SINE } 2\phi$$

The constants of integration A,B,C,D are determined from the conditions of Eqn. 2-9 for the outer boundary and from the condition that the wall of the hole is free from external forces. These conditions give

$$2A + 6C/b^4 + 4D/b^2 = -S/2$$

$$2A + 6C/a^4 + 4D/a^2 = 0$$

$$2A + 6Bb^2 - 6C/b^4 - 2D/b^2 = S/2$$

$$2A + 6Ba^2 - 6C/a^4 - 2D/a^2 = 0$$

For an infinitely large plate $a/b = 0$. These four equations can then be solved to yield $A=-S/4$, $B=0$, $C=-a^4.S/4$, $D=a^2.S/2$. These constants can now be substituted into equation 2-12, and by adding the stresses produced by the uniform compression S/2 on the outer boundary we obtain

$$S_r = S/2\,.(1-a^2/r^2) + S/2.(1+3a^4/r^4 - 4a^2/r^2).\cos 2\phi$$

as radial stress

$$S_\phi = S/2.(1+a^2/r^2)-S/2.(1+3.a^4/r^4).\cos 2\phi \text{ --------------- } 2\text{-}13$$

as the tangential stress and

$$T_{r\phi} = -S/2.(1-3a^4/r^4+2a^2/r^2).\sin 2\phi$$

as the shearing stress, where the stresses are expressed in polar co-ordinates with the centre of the hole as the origin and the plane stress components are at a point (ϕ, r) exterior to the hole of radius <u>a</u> in a plate under uniform uniaxial stress, with ϕ measured from the axis of the compressive stress S.

If $r>>a$, S_r and $T_{r\phi}$ approach the values given in equation 2-9. At the edge of the hole r=a we find

$$S_r = T_{r\phi} = 0 \; ; \; S_\phi = S-2S.\cos 2\phi \text{ ------------------------- } 2\text{-}14$$

It can be seen from (2-14) that S_ϕ is greatest when $\emptyset = \pi/2$ or $3.\pi/2$ (i.e. when $\cos 2\emptyset = -1$) that is at the ends m and n of the diameter perpendicular to the direction of the compression. At these points $(S_\phi)_{max} = 3S$ which is the maximum compressive stress and is three times the uniform stress S applied at the end of the plate. At the points p and q, $\emptyset$ is equal to and 0 and we find $S_\phi = -S$. So there is a tensional stress, resulting from the applied compression, in the tangential direction at these points. For the cross section of the plate through the centre of the hole and perpendicular to the x-axis, $\emptyset = \pi/2$ and from Equation 2-13

$T_{r\phi} = 0$; $S_\phi = S/2.(2+a^2/r^2+3a^4/r^4)$ ------------------2-15

It is clear that the effect of the hole is of a very localised character, and as r increases the stress approaches the value S very rapidly, within a few hole diameters. The distribution of this stress S_ϕ as a function of r is shown in the Fig. 12 by the shaded area, regardless of the relative isotropy of a material. Having the solution equation 2-13 for compression or tension in one direction, the solution for compression or tension in two perpendicular directions can be easily obtained by superposition, of stresses given by (2-13) with $(\emptyset+90)$ for the angular co-ordinate.

A closer approximation to the geological situation is shown in Fig. 13 where unequal compressions S and s, S>s, are applied orthogonally to a plate with a small hole in it.

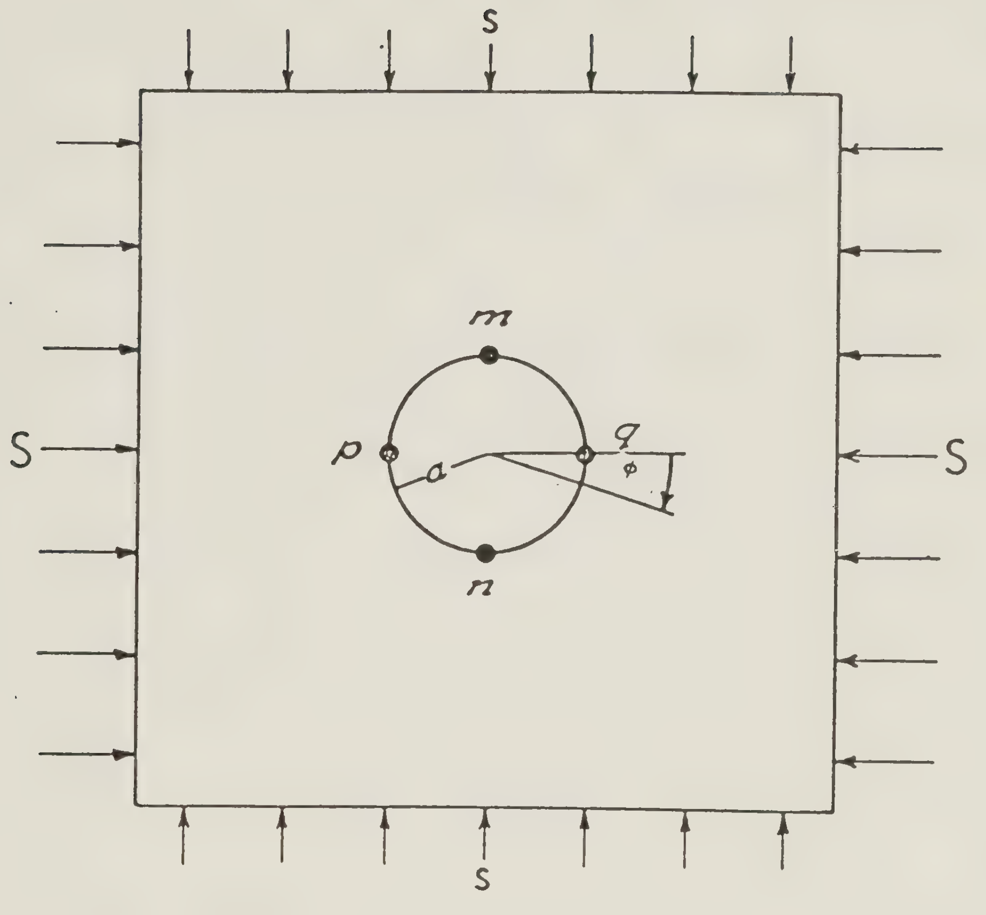


Figure 13.... A plate submitted to two compressions S and s with a small circular hole in it

At the hole boundary r=a, it follows from the superposition that

$S_r = T_{r\phi} = 0$; $S_\phi = S+s-2(S-s)\cos 2\phi$ ----------------------- 2-16

and S_ϕ is maximum, when $\cos 2\phi = -1$ with value $(3S-s)$ when $\phi = \pi/2$, $3.\pi/2$ (at m, n), and minimum when $\cos 2\phi = 1$, with value $(3s-S)$ when $\phi = 0, \pi$ (at p, q).

Where measurements have been made, horizontal principal stresses in the upper crust range from equality S=s to about S=4s or more (McGarr and Gay, 1978). The values of the horizontal stresses across the principal planes in the neighbourhood of the borehole have been calculated by Gough and Bell (1982) for various relative values of the S/s ratio and are shown in Figures 14 and 15. Figures 14 A and B show the individual stress distributions. The principle of the superposition of the two parts of the stress field is illustrated in Fig. 14 C for the case in which S/s =1.0 . For S alone the tangential stress at the walls of the hole varies from a minimum value of -S (tensile) across the plane parallel to the S-axis to a maximum of +3S, across the plane normal to the S-axis. With the superposition, the stress field has radial symmetry and the tangential stress at the wall of the hole is +2S as can also be deduced from the equation 2-16. From equation 2-16 when S_ϕ = 2S = 2s, it is independent of ϕ and so failure may occur but without a preferred azimuth. As the ratio of S to s approaches one, the determination of the magnitudes and directions of S and s becomes less reliable because of the lack of resolution.

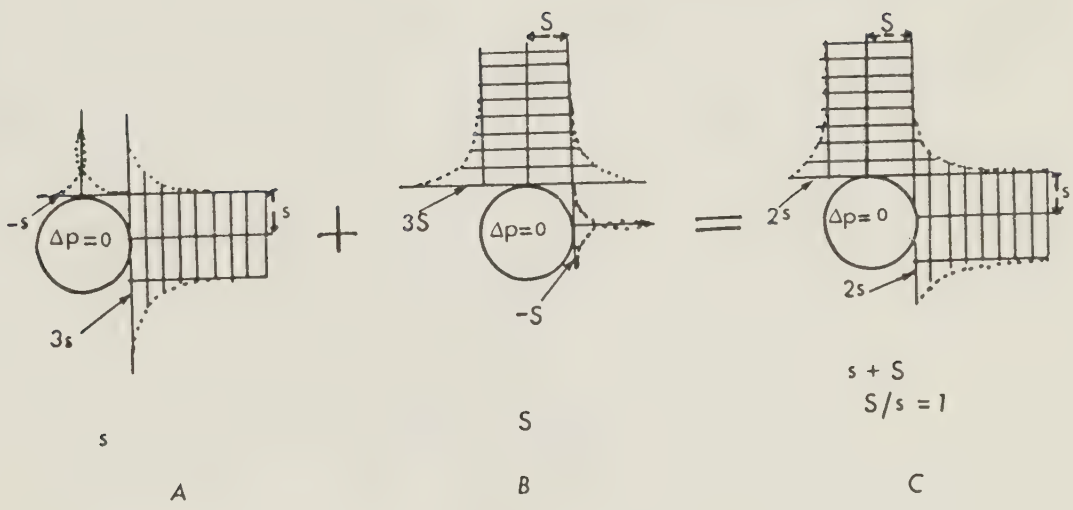


Figure 14.... Superposition of stress states about a borehole due to two horizontal principal stresses of equal magnitude.

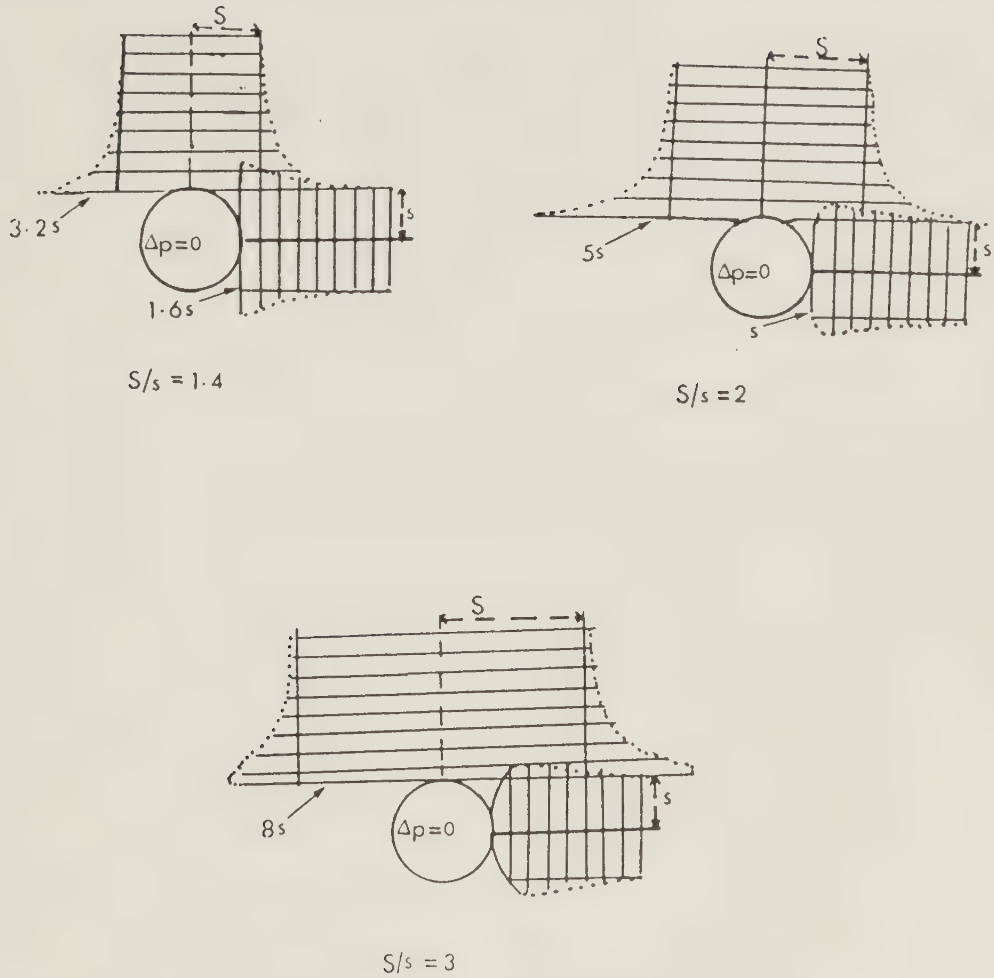


Figure 15.... Stress states about a borehole for regional stress-ratios S/s of 1.4, 2.0, and 3.0.

The resultant stress fields for other ratios of S/s are shown in figure 15. For the case when S/s = 3.0 the tangential stress at the walls of the hole varies from a minimum of 0 to a maximum of +8s (see Eqn. 2-16).

III. DATA COLLECTION AND ANALYSIS

Data have been secured from wells distributed widely in the sedimentary basin of Alberta as shown in Figure 16. In analysing the records it was observed that in depth ranges characterised by oversized holes, the tool tended to rotate in some parts and ceased to rotate in other parts. On the other hand, the tool ceased to rotate in certain ranges in which the two orthogonal diameters were equal indicating a circular cross-section. Such observations led to the adoption of three criteria to be used in identifying breakouts. These are:

1. The tool ceases to rotate, with the azimuth of the No. 1 electrode approximately constant.
2. The two orthogonal diameters are definitely unequal with the smaller diameter at bit size.
3. The tool was rotating both below and above the breakout zone. This ensures that the rotation was stopped by the breakout and not by some other cause.

The application of these three criteria causes the rejection of many elongated zones,but ensures that only definitely identified breakouts are used in the study. Table 3.1 lists the breakouts identified by means of these three criteria, from the available log records.

Representation and Statistics of Angular Data

We wish now to combine the various mean azimuths of the breakouts in order to obtain a representative breakout azimuth for each well. We may regard an angular observation

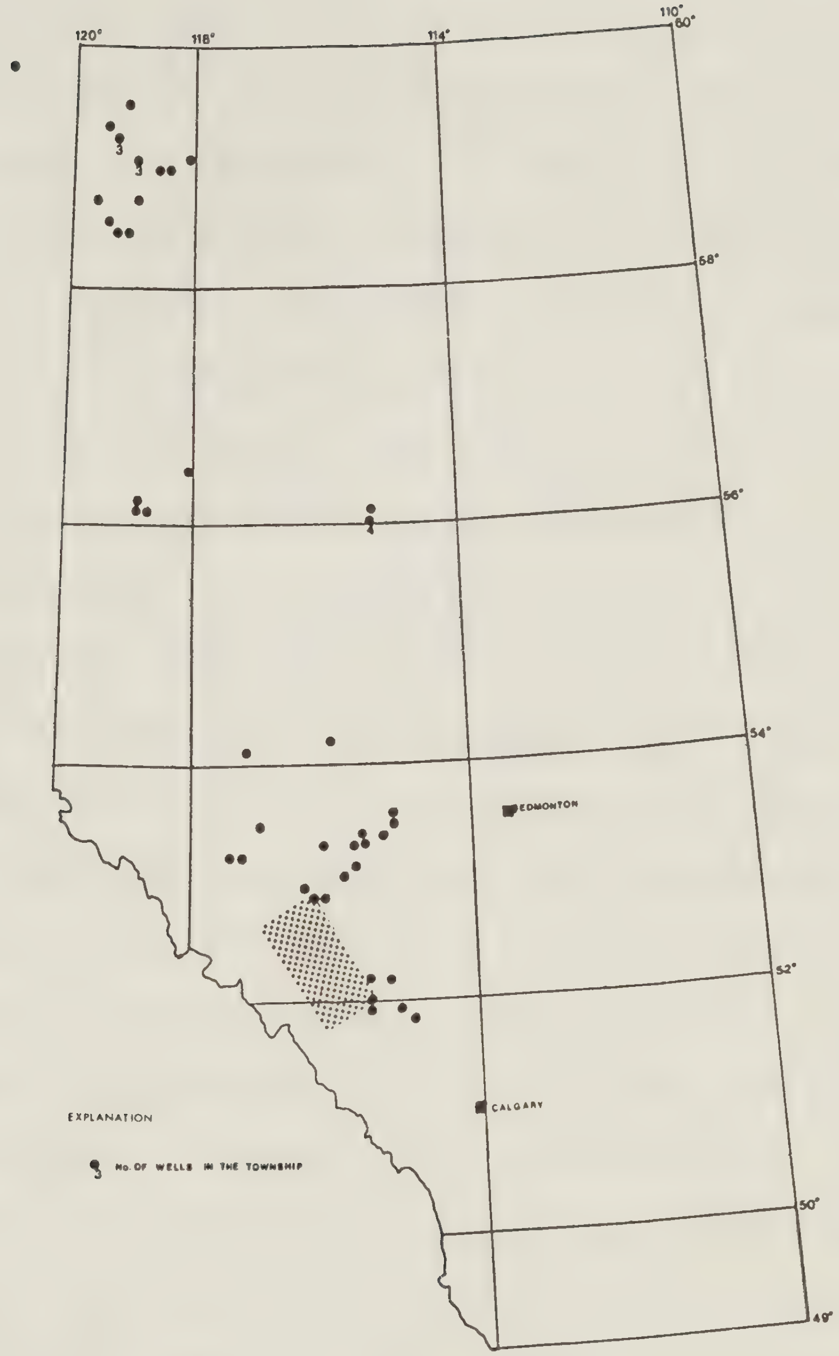


Figure 16.... Map of Alberta showing locations of wells analysed in this study

as a point on a circle of unit radius. A single observation $\emptyset$ ($0° \leq \emptyset \leq 360°$) measured in degrees is then a unit vector and the data can be described as circular data. If the vector is not directed , i.e if the angles $\emptyset$ ($0° \leq \emptyset \leq 180°$) and $180°+\emptyset$ are not distinguished, the data can be described as *axial or non-polar* data. Ungrouped angular data can be represented in two ways; (a) by points on the circumference of a unit circle , the same weight being assigned to each observation, or (b) by drawing the radii of a unit circle obtained by joining the origin to the observed points on the circumference,(figure 17).

Alternatively, angular data can be grouped by dividing the range 0 to 360 degrees into a certain number of class intervals. The frequency is then the number of observations within each class. The data can then be represented on a histogram similar to that used on a line, by constructing a block whose area is proportional to the frequency in that interval on the circumference of a unit circle. This diagram is called a *circular histogram.* This histogram can also be unrolled so that it sits on a straight line divided into the class intervals. The point of cut for unrolling the unit circle needs careful selection. For data that have a mode (a preferred direction) it is reasonable to use a cut such that the centre of the linear histogram approximately corresponds to this mode to avoid division of the modal peak between the ends of the histogram. This linear histogram is preferred to the circular histogram mainly because it is easier to

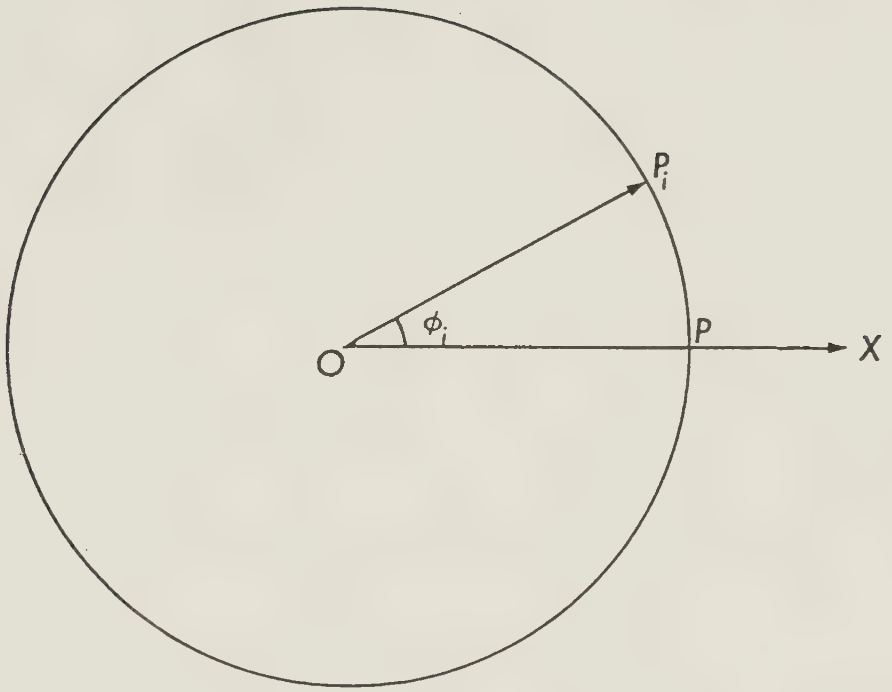


Figure 17.... Representations of the ith sample point ϕ_i
OP=1

evaluate.

Another natural representation of angular data is a Rose diagram. In this approach we construct a sector, corresponding to each class interval, with apex at the origin and radius proportional to the class frequency (and arc substending the class interval). A disadvantage of this representation is that the area of each sector is proportional to N^2, where N is the frequency, so that the data appear much better grouped than they really are. However, the Rose diagram is widely used in geology.

A Measure of Location

In the first instance it is tempting to use the conventional measures on the line for a circular distribution. Let us consider a case where we have a sample of size 2 and the observed angles are 1° and 359°. The arithmetic mean and the sample variance give unreasonable results. Intuitively, however, we infer the mean direction and the deviation about the mean to be in some sense 0° and 1° respectively. A sensible answer, however, results if we select the zero direction as the y-axis in place of the x-axis. This will then reduce the data to 269° and 271°. Hence, the usual linear measures depend heavily on the choice of the zero direction and will not be appropriate for circular distributions. Let $X_1, \ldots\ldots, X_n$ be n observations on the line and let $X_1', \ldots\ldots\ldots\ldots\ldots, X_n'$ represent the same observations when the distances are measured from O' instead of the origin O along the x-axis. Let OO'= a. If L is a

suitable measure of location on the line we should have

$L(X_1',\ldots,X_n') = L(X_1,\ldots,X_n) - a$ --------------------3-1

which implies that the position of the point whose x-coordinate is $L(X_1,\ldots,X_n)$ remains invariant under the choice of origin. Similarly it is desirable that the measure of circular location should not depend upon the choice of the zero direction.

Let $\varnothing_1',\ldots,\varnothing_n'$ be the angles obtained from $\varnothing_1,\ldots,\varnothing_n$ with respect to a new zero direction OA. If angle XOA = α, then we have

$L(\varnothing_1',\ldots,\varnothing_n') = (L(\varnothing_1,\ldots,\varnothing_n) - \alpha) \bmod 2\pi$--------------------3-2

The contrast between Equations 3-1 and 3-2 indicates the different natures of the problems on the line and on the circle.

The Mean Direction

Suppose P_i is the point on the circumference of a unit circle corresponding to the angle $\varnothing_i$, i = 1,...,n. Then the mean direction $\bar{\varnothing}$ of $\varnothing_1,\ldots,\varnothing_n$ is defined as the direction of the resultant of the unit vectors $\bar{OP}_1,\ldots,\bar{OP}_n$. The cartesian coordinates of P_i are $(\cos\varnothing_i, \sin\varnothing_i)$ so that the centre of gravity of these points is $(\bar{C}, \bar{S})$ such that

$\bar{C} = 1/n.\Sigma\cos\varnothing_i$; $\bar{S} = 1/n.\Sigma\sin\varnothing_i$ -------------------------3-3

If $\bar{R} = \sqrt{(\bar{C}^2 + \bar{S}^2)}$ --3-4

then $R = n\bar{R}$ is the length of the resultant and $\bar{\varnothing}$ is the solution of the equations

$\bar{C} = \bar{R}.\cos\bar{\varnothing}$; $\bar{S} = \bar{R}.\sin\bar{\varnothing}$------------------------------------3-5

It can be shown that $\bar{\varnothing}$ has some desirable properties as a

measure of location.(see Appendix A)

The Circular Variance

Let P_i be the point corresponding to ϕ_i on a unit circle and α be a fixed direction. If we assume initially that $\alpha=0$ and suppose that P is the corresponding point on the circle then a measure of the circular dispersion between P and P_i is the smaller of the two angles that OP_i makes with OP, say β_i (see Fig. 17). We have

$$\beta_i = \min(\phi_i, 2\pi - \phi_i) = \pi - |\pi - \phi_i| \quad \text{------------------------3-6}$$

$1-\cos\beta_i$ is an increasing function of β_i. Let

$$D = 1/n \,.\, \Sigma(1-\cos\beta_i), \; i = 1,..,n \quad \text{---------------------3-7}$$

be a measure of the dispersion of the points P_i. After shifting the zero direction to α using

$$\phi_i' = (\phi_i - \alpha) \bmod 2\pi,$$

we can write

$$D=1/n \,.\, \Sigma(1-\cos(\phi_i - \alpha)) \quad \text{-----------------------------------3-8}$$

The dispersion D is minimised at $\alpha=\bar{\phi}$. If we equate the derivative of (3-8) with respect to α to zero we have

$\Sigma\sin(\phi_i - \alpha)=0$, so that the dispersion is smallest about $\bar{\phi}$ (see Appendix A Equations A-1 and A-6.). This is similar to the expression for the ordinary sample variance. D can be written about $\bar{\phi}$ as S_0 where

$$S_0 = 1-1/n \,.\, \Sigma\cos(\phi_i - \bar{\phi}) \quad \text{-------------------------------3-9}$$

which can be simplified to

$$S_0 = 1 - \bar{R} \quad \text{--3-10}$$

S_0 is called the circular variance and $\bar{R}$ is the mean resultant vector magnitude. From (A-5), it can be seen that

S_0 is invariant under a change of the zero direction. Let R be the length of the resultant of the vectors OP_i i.e. $R = n.\bar{R}$ so that

$S_0 = 1 - R/n$ ------------------------------------3-11

Thus we see immediately that

$0 \leq S_0 \leq 1.0$------------------------------------3-12

Since R tends to n for tightly grouped unit vectors, clearly S_0 tends to 0 for tight distributions and S_0 tends to 1.0 for random distributions. From (3-12) S_0 takes values in (0,1) unlike σ^2 for linear data whose range is (0,infinity). An appropriate transformation (first suggested by Von Mises in 1918) of S_0 to the range (0,infinity) is given by

$\sigma = \sqrt{(-2.\log_e(1 - S_0))}$ ------------------------------------3-13

In (3-13) it has been assumed that the range of $\emptyset$ is $(0,2\pi)$. If the range of $\emptyset$ is $(0,2\pi/L)$ then we define

$\sigma = (-2\log_e(1 - S_0))^{1/2}/L$.

For grouped data we have

$\bar{C} = 1/n .\sum f_i .\cos\emptyset_i$; $\bar{S} = 1/n.\sum f_i .\sin\emptyset_i$, and $\bar{R} = (\bar{C}^2 + \bar{S}^2)^{1/2}$.

Then $\cos\bar{\emptyset} = \bar{C} / \bar{R}$; $\sin\bar{\emptyset} = \bar{S}/ \bar{R}$, $S_0 = 1 - \bar{R}$.

To obtain $\bar{\emptyset}$ it is convenient to use

$\bar{\emptyset} = \bar{\emptyset}'$ if $\bar{S} > 0$, $\bar{C} > 0$ (1st quadrant)

$\bar{\emptyset} = \bar{\emptyset}' + \pi$ if $\bar{C} < 0$, $\bar{S} > 0$ (2nd quadrant)

$\bar{\emptyset} = \bar{\emptyset}' + \pi$ if $\bar{C} < 0$, $\bar{S} < 0$ (3rd quadrant)

$\bar{\emptyset} = \bar{\emptyset}' + 2\pi$ if $\bar{S} < 0$, $\bar{C} > 0$ (4th quadrant)

where $\bar{\emptyset}' = \arctan(\bar{S} / \bar{C})$, and $-\pi/2 < \bar{\emptyset}' < \pi/2$. For axial (non-polar) data, in the range (0°-180°), we first double

the angles to maintain the periodicity. Thus we have $\emptyset_i' = 2.\emptyset_i$ and carry out the calculations using the equations already listed, and the frequencies f_i corresponding to the mid-points $\emptyset_i'$. Suppose $\bar{C}'$, $\bar{S}'$, $\bar{\emptyset}'$ etc. are the quantities for $\emptyset_i'$ corresponding to $\bar{C}$, $\bar{S}$, $\bar{\emptyset}$ etc. then an appropriate measure of the circular mean $\bar{\emptyset}$ for the $\emptyset_i$ can be taken as $\bar{\emptyset} = \bar{\emptyset}'/2$ and an appropriate measure of the circular variance S_0 for $\emptyset_i$ is $S_0 = 1-(1-S_0')^{1/4}$. In general if the range of $\emptyset$ is $(0\ ,\ 2\pi/L)$ we have

$$S_0 = 1 - (1 - S_0')^{1/L^2} .$$

The result of applying these statistics to the raw azimuth data measured at every two feet depth interval within an identified breakout is shown in the column headed MEAN in Table 3.1 and also in columns 8 and 9 of Table 3.2. Table 3.2 shows the mean orientation of the various breakout zones in a well.

Statistical Decision

We are now near a position to make inferences on our data. Before making any inferences, however, we wish to look at the problem of the *regression* of one variable, in our case the azimuth, on another variable (independent variable), which is the depth in our situation. We shall then look at the correlation or the degree of relationship between the variables. We first consider the problem of how well a straight line explains the relationship between two variables. This requires the equation for the Least Square Regression Line. The least square regression line of Y on X

TABLE 3.1

Breakout azimuths in relation to rock types and age of rocks. (All lengths are in feet except where indicated).

e attached to a breakout depth range indicates that a section of the range shown does not satisfy the three criteria. N is number of observations.

WELL 6-30-46-17W5 80 ELONGATIONS 51 BREAKOUTS

ELONGATED INTERVALS		BREAKOUT INTERVALS				STRATIGRAPHIC INFORMATION			
DEPTH RANGE	LENGTH	DEPTH RANGE	LENGTH	N	MEAN AZIMUTH(DEG)	PERIOD	Fm. TOP	FORMATION	LITHOLOGY
3229-3541	312	3254-3521e	174	28	138.0				
3719-3750	31	3722-3732	10	3	134.3				
3754-3792	38	3760-3790	30	6	51.2				
3816-4069	253	3828-4050e	178	32	137.3				
4076-4145	69	4106-4120	14	4	74.5				
4186-4526	340	4212-4488e	244	39	11.6				
4564-4646	82	4584-4630e	22	10	141.4				
4659-4728	69	4662-4724	62	9	149.9				
4730-4762	32	30-40,56-62	16	5	153.0				
4861-5144	283	4862-5132e	174	30	145.9				
5147-5176	29	5150-5168	18	3	139.7				
5228-5336	108	5246-5332e	24	10	142.7				
5340-5370	30	5352-5368	16	5	39.2				
5526-5820	294	5546-5812e	160	40	144.9				
5852-5935	83	5852-5922	70	14	142.2				
5982-6002	20	5984-5996	12	3	34.3				
6004-6053	49	6004-6028	24	7	154.1				
6058-6075	17	6058-6072	14	4	35.0				
6100-6340	240	6156-6320e	94	26	162.6				
6374-6452	78	6394-6438e	28	8	78.0				
6504-6526	22	6514-6522	8	3	150.3				
6546-6576	30	6548-6570	22	4	75.5				
6607-6781	174	6610-6744e	82	18	140.5				
6785-6804	19	6786-6796	10	3	152.3				
6814-7076	262	6920-7028e	46	12	157.8				
7118-7192	74	18-30,72-84	24	6	158.5				
7208-7243	35	7216-7230	14	3	135.7				
7350-7448	98	68-80,7412-26	26	8	139.8				
7450-7558	108	7494-7504	10	5	142.0				
7615-8006	391	7710-7995e	152	36	135.4	U.CRETACEOUS	7734	LEA PARK	
8034-8385	351	8036-8378e	280	49	151.7	U. CRE.		LEA PARK	
8426-8840	414	8430-8838e	400	49	154.1	U. CRE.		LEA PARK	
8848-8874	26	8854-8866	12	3	78.3	U. CRE.		LEA PARK	
8876-9210	334	8978-9162e	128	20	134.3	U. CRE.	/9066/9204	LEA/CARD ZN/CARD SD	
9226-9284	58	9244-9274	30	4	141.5	U. CRE.	9204	CARD SD	
9346-9354	8	9346-9350	4	2	142.0	U. CRE.	9322	BLKSTN	
9430-9436	6	9430-9436	6	3	141.0	U. CRE.		BLKSTN	
9491-9553	62	9498-9512	14	3	54.7	U. CRE.		BLKSTN	
9576-9645	69	32-38,40-44	10	5	91.2	U. CRE.		BLKSTN	
9663-9672	9	9666-9672	6	3	129.0	U. CRE.		BLKSTN	
9701-9995	294	9718-9976e	128	27	131.6	U. CRE.		BLKSTN	
10006-10319	313	10006-10252e	68	15	133.4	U. CRE.		BLKSTN	
10359-10759	400	10368-10758e	164	29	118.9	L. CRE.	/10583/10672/10754	BLKSTN/BFS/VIK/BLAIR	
10800-10844	44	10804-10808	4	2	169.0	L. CRE.	10754	BLAIR	
11000-11050	50	11008-11020	12	5	28.2	L. CRE.		BLAIR	
11411-11424	13	11414-11418	4	2	141.0	L. CRE.		BLAIR	
11810-11826	16	11812-11820	8	4	144.5	L. CRE.	11456	BLUESKY	
11830-11848	18	11834-11842	8	4	133.5	L. CRE.		BLUESKY	
11896-11905	9	11898-11904	6	3	148.7	JURASSIC	11892	ROCK CK	
11926-11956	30	11944-11948	4	2	146.0	JURASSIC		ROCK CK	
11970-11980	10	11970-11976	6	3	129.3	JURASSIC		ROCK CK	

ELONGATION ENDS 12010, LO FERNIE ; TOTAL DEPTH 15820 CAMBRIAN PROD. ZONE LO BLAIR.

WELL 7-9-49-24W5 144 ELONGATIONS 71 BREAKOUTS

ELONGATED INTERVALS		BREAKOUT INTERVALS				STRATIGRAPHIC INFORMATION			
1481-1503	22	1487-1497	10	5	146.0				
1511-1535	24	1531-1535	4	3	146.3				
1713-1921	208	1719-1913e	114	60	89.3				
1963-2018	55	1967-2011e	28	14	135.6				
2097-2153	56	2101-15,23-27	20	10	135.7				
2158-2221	63	69-79,97-2221	36	18	82.9				
2257-2295	38	2257-2273	16	9	91.0				
2315-2327	12	2317-2327	10	6	143.6				
2351-2457	106	2383-2451e	52	23	136.3				
2551-2587	36	2567-2575	8	5	73.0				
2606-2683	77	2667-2681	14	8	60.0				
2759-2820	61	69-89,95-2809	34	18	114.3				
2970-3588	618	2979-3527e	366	189	170.2	U.CRETACEOUS	3260	WAPIABI	....
3590-3643	53	3591-3599	8	5	67.2	U. CRE.		WAPIABI	....
3681-3963	282	3683-5107e	268	45	29.5	U. CRE.		WAPIABI	....
3967-3973	[illegible]	3967-3973	6	4	39.0	U. CRE.		WAPIABI	....
4009-4087	78	4055-4069	14	8	119.1	U. CRE.		WAPIABI	....
4198-4222	24	4201-4217	18	10	125.0	U. CRE.	4160	BADH	....
4228-4276	48	39-61,71-75	26	15	133.7	U. CRE.		BADH	....
4277-4334	57	77-89,97-4321	36	20	38.9	U. CRE.		BADH	....
4346-4427	81	4377-4417	40	21	22.8	U. CRE.		BADH	....
4450-5107	657	4509-5003e	62	38	162.2	U. CRE	/4550/4710	BADH/F BADH/2nd BADH	....
5300-5880	580	5309-5875e	96	55	79.1	U.CRE.	5286/5640	CARD SD/BLKSTN	....
5926-7311	1383	5983-7309e	248	128	136.8	U. CRE.	7220	BLKSTN/BFS	....
7312-7676	364	7313-7567e	60	30	134.1	L. CRE.	7310/7460/7565	F BFS/2nd BFS/MTN PARK	....
7682-7704	22	7683-7697	14	7	123.1	L. CRE.	7565	MTN PARK	....
7710-7840	130	7717-7811e	22	11	130.5	L. CRE.		MTN PARK	....
7857-7967	110	7861-7883	22	11	146.6	L. CRE.		MTN PARK	....
7984-8046	62	7989-7997	8	4	49.8	L. CRE.		MTN PARK	....
8102-8124	22	8107-8115	6	3	88.0	L. CRE.		MTN PARK	....
8202-8221	19	8207-8213	6	3	144.6	L. CRE.		MTN PARK	....
8242-8255	13	8245-8251	6	3	134.0	L. CRE.		MTN PARK	....
8300-8316	16	8301-8311	10	5	143.2	L. CRE.		MTN PARK	.....
8360-8498	138	8445-8451	6	3	55.3	L. CRE.		MTN PARK	.....
8360-8498	0	8459-8479	20	10	146.1	L. CRE.		MTN PARK	....
8740-8792	52	55-63,67-71	12	6	168.0	L. CRE.		MTN PARK	....
9469-9497	28	9471-9477	6	3	127.3	L. CRE.	8910	LUSCAR	....
9545-9555	10	9549-9555	6	3	96.3	L. CRE.		LUSCAR	....
10321-10358	37	10333-10339	6	3	2.0	L. CRE.	9839	2nd LUSCAR COAL	COAL
10376-10415	39	10383-10387	4	2	112.0	L. CRE.		2nd LUSCAR COAL	COAL
10478-10549	71	10491-10549	58	29	160.6	L. CRE.		2nd LUSCAR COAL	COAL
10563-10685	122	10563-10659e	66	34	53.0	L. CRE.		2nd LUSCAR COAL	COAL
10687-10857	169	10705-10835e	86	45	159.8	L. CRE.		2nd LUSCAR COAL	COAL
10860-10893	33	10863-10867	4	2	133.5	L. CRE.		2nd LUSCAR COAL	COAL
10916-10923	7	10919-10923	4	2	55.0	L. CRE.		2nd LUSCAR COAL	COAL
10999-11133	134	11021-11071	50	25	125.6	L. CRE.		2nd LUSCAR COAL	COAL
11143-11167	24	11147-11155	8	4	154.3	L. CRE.		2nd LUSCAR COAL	COAL
11173-11195	22	11177-11185	8	4	141.0	L. CRE.		2nd LUSCAR COAL	COAL
11217-11252	35	11219-11223	6	3	154.7	L. CRE.		2nd LUSCAR COAL	COAL
11442-11527	85	11457-11501e	24	12	177.2	L. CRE.		2nd LUSCAR COAL	COAL
11545-11570	25	11553-11569	16	9	35.4	L. CRE.		2nd LUSCAR COAL	COAL
11573-11703	130	11657-11685	28	14	33.4	L. CRE.		2nd LUSCAR COAL	COAL
11720-11799	79	11737-11791e	56	29	180.0	L. CRE.		2nd LUSCAR COAL	COAL
11801-11858	57	11801-11833e	22	11	156.3	L. CRE.		2nd LUSCAR COAL	COAL
12035-12065	30	12047-12059	12	6	146.5	L. CRE.		2nd LUSCAR COAL	COAL
12129-12150	21	12133-12141	8	4	142.8	L. CRE.		2nd LUSCAR COAL	COAL
12270-12295	25	12291-12297	6	3	134.3	L. CRE.		2nd LUSCAR COAL	COAL
12387-12403	16	12397-12401	4	2	69.0	L. CRE.		2nd LUSCAR COAL	COAL
12410-12419	9	12413-12417	4	2	147.5	L. CRE.		2nd LUSCAR COAL	COAL
12650-12683	33	12665-12675	10	5	45.6	L. CRE.		2nd LUSCAR COAL	COAL
12713-12798	85	12723-12735	12	6	174.0	L. CRE.		2nd LUSCAR COAL	COAL
12713-12798	0	12761-12765	4	2	96.5	L. CRE.		2nd LUSCAR COAL	COAL
12813-12953	140	55-91,12943-47	40	20	135.8	L. CRE.		2nd LUSCAR COAL	COAL
12965-13000	35	69-83,89-93	18	9	154.8	L. CRE.		2nd LUSCAR COAL	COAL
13022-13040	18	13025-13029	4	2	174.0	L. CRE./JURASSIC		2nd LUSCAR COAL	COAL
13276-13281	5	13277-13281	4	2	44.0	JURASSIC	13130	NIKANASIN	....
13480-13496	16	13491-13495	4	3	163.7	JURA.		NIKANASIN	....
13502-13512	10	13505-13511	6	3	152.7	JURA.		NIKANASIN	.....
13537-13554	17	13549-13553	4	2	137.0	JURA		NIKANASIN	....
13822-13851	29	13837-13845	8	4	136.5	JURA.		NIKANASIN	....
13856-13887	31	13871-13873	2	1	152.0	JURA.		NIKANASIN	....

ELONGATION ENDS 13887,NIKANASIN ; TOTAL DEPTH *****, NIKANASIN; D&A

WELL 12-19-53-8W5 11 ELONGATIONS 10 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC	INFORMATION		
6489-6550	61	6506-6540	32	16	117.9				
6606-6636	30	6606-6636e	20	10	121.3				
6706-6736	30	6712-6736	24	10	119.7				
6746-6780	34	6746-6774	28	14	119.4				
6854-6882	28	6854-6882	28	14	124.4				
6910-6980	70	32-36,40-72	36	18	127.6				
7226-7280	54	28-44,54-74	36	18	124.9				
7410-7458	48	7412-7456	46	23	125.7				
7513-7530	17	7516-7524	8	4	137.5				
7782-7800	18	7792-7796	4	2	145.0				

WELL b-45-A-94-P-14 13 ELONGATIONS 6 BREAKOUTS

5726-5729	3	5727-5729	2	1	149.0	U. DEVONIAN	4328	FT. SIMP	----
5845-5858	13	5845-5851	6	5	158.3	U. DEV.		FT. SIMP	----
5883-5895	12	5885-5893	8	5	68.5	U. DEV.		FT. SIMP	----
5913-5923	10	5913-5921	8	4	63.8	U. DEV.		FT. SIMP	----
5930-5938	8	5931-5937	6	3	53.7	U. DEV.		FT. SIMP	----
5954-5958	4	5955-5957	2	1	61.0	U. DEV		FT. SIMP	-----

ELONGATION ENDS 5958, FT. SIMP; TOTAL DEPTH 6089, SLAVE POINT-6050 PROD. ZONE, SLAVE POINT.(L DEV.)

WELL 6-12-50-11W5 m 18 ELONGATIONS 12 BREAKOUTS

2480-2497	17	81-87,89-97	14	13	120.4	MISSI/U.DEV	2318/2481	BANFF/WABAMUN	-----
2497-2505	8	2497-2505	8	8	129.3	U. DEV		WABAMUN	-----
2507-2516	9	2507-2512	5	5	125.6	U. DEV.		WABAMUN	-----
2526-2535	9	2528-2535e	4	4	124.3	U. DEV.		WABAMUN	-----
2535-2582	47	2536-2577e	24	24	121.7	U. DEV		WABAMUN	-----
2585-2588	3	2585-2588	3	3	133.0	U. DEV.		WABAMUN	-----
2596-2611	15	2608-2610	2	2	123.0	U. DEV		WABAMUN	-----
2615-2627	12	2615-2619	4	4	128.5	U. DEV.		WABAMUN	----
2675-2680	5	2675-2678	3	3	132.0	U. DEV.		WABAMUN	-----
2702-2720	18	06-07,10-18	9	5	132.0	U. DEV.	2699	BLUERIDGE	-----
2721-2731	10	2722-2730	8	8	137.6	U. DEV.		BLUERIDGE	-----
2731-2735	4	2732-2735	3	3	136.0	U. DEV.		BLUERIDGE	----

ELONGATION ENDS 2874, IRETON ;TOTAL DEPTH 2876,IRETON=2858 ; PROD. ZONE, NISKU =2736m (U. DEV)

WELL 14-20-50-12W5 28 ELONGATIONS 24 BREAKOUTS

7425-7429	4	7425-7429	4	2	129.5	L. CRETACEOUS	7030	BLAIR	----
7433-7439	6	7433-7435	2	1	123.0	L CRE.		BLAIR	----
7465-7547	82	7477-7548e	54	26	126.2	L. CRE.	/7527	BLAIR/GLAUC	----
7577-7596	19	7584-7590	6	3	124.7	L. CRE.	7569	L MANV	-----
7651-7709	58	7652-7704	52	23	122.9	JURASSIC	7626/7677	BSL Q/U FERNIE	----
7717-7737	20	18-24,28-36	14	7	127.3	JURA.	7707	ROCK CK SS.	SS.
7751-7783	32	7752-7780	28	10	125.2	JURA.		ROCK CK SS.	SS.
7827-7868	41	28-36,48-64	24	18	120.0	JURA.	7828	FERNIE SHALES	SHALES
8148-8156	8	8150-8156	6	3	120.3	MISSISSIPP.	8150	BANFF	-----
8181-8197	16	8188-8196	8	4	108.5	MISS.		BANFF	----
8215-8237	22	8218-8228	10	5	108.6	MISS.		BANFF	----
8255-8272	17	8256-8268	12	6	108.6	MISS.		BANFF	----
8280-8295	15	8286-8290	4	2	119.0	MISS.		BANFF	----
8445-8454	9	8446-8452	6	3	120.0	MISS.		BANFF	----
8678-8848	170	8696-8814e	56	20	124.7	U. DEVONIAN	8680	WABAMUN	-----
8851-8864	13	8852-8862	10	5	4.0	U. DEV.		WABAMUN	----
8895-8913	18	8896-8910	14	7	123.7	U. DEV.		WABAMUN	----
8937-8945	8	8938-8942	4	2	118.0	U. DEV.		WABAMUN	----
8949-8983	34	8968-8974	6	3	124.3	U. DEV.		WABAMUN	----
9097-9138	41	9100-9138e	30	15	119.3	U. DEV		WABAMUN	----
9207-9227	20	9208-9214	6	3	120.5	U. DEV.		WABAMUN	-----
9237-9251	14	9238-9242	4	2	131.0	U. DEV.		WABAMUN	----
9387-9473	86	9388-9464e	48	24	117.0	U. DEV.	9388	BLUERIDGE	-----
9487-9501	14	9488-9498	10	5	124.4	U DEV		BLUERIDGE	-----

ELONGATION ENDS 9501, BLUERIDGE; TOTAL DEPTH 11537, CAMBRIAN=11483 PROD. ZONE NISKU=9532 / L MANV=7569.(U.DEV/L.CRE)

WELL 4-26-51-11W5 2 ELONGATIONS 2 BREAKOUTS

8585-8607	22	8585-8605	20	11	128.1	U. DEVONIAN	8523	WINTERBURN/GRAMINIA	----
8631-8665	34	8631-8663	32	17	114.6	U. DEV.	8652	CALMAR	----

ELONGATION ENDS 8665,CALMAR ;TOTAL DEPTH 9120 IRETON=9082 PROD. ZONE NISKU=8682

WELL 3-32-47-13W5 28 ELONGATIONS 23 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC	INFORMATION		
9579-9599	20	9579-9587	8	4	108.8	MISSISSIPPIAN	9522	PEKISKO	....
9619-9733	114	9619-9733	114	58	119.1	MISS.	/9661	PEKISKO/BANFF	....
9735-9757	22	9735-9749	14	8	125.0	MISS.		BANFF	....
9797-9833	36	9805-9827	22	12	113.3	MISS.		BANFF	....
9847-9871	24	9849-9867	18	10	119.3	MISS.		BANFF	....
9887-9909	22	9889-9908	18	10	134.5	MISS.		BANFF	....
10179-10261	82	10181-10259	78	40	125.0	U. DEVONIAN	10180	WABAMUN	....
10267-10279	12	10267-10273	6	3	131.0	U. DEV.		WABAMUN	....
10391-10403	12	10391-10399	8	4	142.8	U. DEV.		WABAMUN	....
10479-10529	50	10501-10527	26	15	141.2	U. DEV.		WABAMUN	....
10555-10651	96	10557-10649e	78	41	157.3	U. DEV.		WABAMUN	....
10667-10695	28	10669-10683	14	7	167.9	U. DEV.		WABAMUN	....
10715-10729	14	10715-10725	10	6	139.0	U. DEV.		WABAMUN	....
10747-10753	6	10747-10751	4	2	134.0	U. DEV.		WABAMUN	....
10767-10771	4	10767-10771	4	2	126.3	U. DEV.		WABAMUN	....
10789-10799	10	10791-10795	4	2	123.0	U. DEV.		WABAMUN	....
10803-10813	10	10807-10813	6	3	158.0	U. DEV.		WABAMUN	....
10847-10857	10	10851-10853	2	1	125.0	U. DEV.		WABAMUN	....
10935-10971	36	10935-10963e	26	14	132.4	U. DEV.	10867	WINTERBURN	....
10973-11011	38	10973-11011	38	20	122.3	U. DEV.		WINTERBURN	....
11133-11155	22	11135-11155	20	11	140.2	U. DEV.	11025	NISKU	....
11161-11165	4	11161-11165	4	2	143.0	U. DEV.		NISKU	....
11171-11179	8	11171-11175	4	2	139.0	U. DEV.		NISKU	....

ELONGATION ENDS 11179,NISKU ;TOTAL DEPTH 11493,IRETON=*****(U.DEV) PROD. ZONE NISKU.

WELL 6-30-48-12W5 13 ELONGATIONS 12 BREAKOUTS

10055-10061	6	10055-10061	6	3	132.3	U. DEVONIAN	9368	WABAMUN	....
10095-10099	4	10095-10099	4	3	134.0	U. DEV.	10095	BLUERIDGE	....
10111-10231	120	11-29,53-10231	96	50	125.7	U. DEV.		BLUERIDGE	....
10245-10259	14	10245-10255	10	5	127.4	U. DEV.	/10246	BLUERIDGE/NISKU	....
10279-10285	6	10279-10283	4	3	132.0	U. DEV.	10246	NISKU	....
10783-10805	22	10785-10799	14	8	141.0	U. DEV.	10536	IRETON	....
10817-10835	18	10817-10833	16	8	132.3	U. DEV.		IRETON	....
10867-10881	14	10869-10877	8	5	142.0	U. DEV.		IRETON	....
10905-10911	6	10905-10909	4	3	129.3	U. DEV.		IRETON	....
11055-11073	18	11055-11073	18	10	137.1	U. DEV.		IRETON	....
11117-11125	8	11117-11121	4	2	151.0	U. DEV.		IRETON	....
11319-11395	76	11321-11393e	58	32	144.6	U. DEV.	11145	DUVERNAY	....

ELONGATION ENDS 11395,DUV ; TOTAL DEPTH 11640, B H L =11402(U.DEV) PROD. ZONE SHUNDA=8658.(MISS.)

WELL 10-25-45-15W5 12 ELONGATIONS 11 BREAKOUTS

10447-10521	74	10475-10517	42	21	142.4	L.CRETACEOUS	9750/10501	BLAIR/ L BLAIR	....
10579-10601	22	10581-10601	20	11	144.7	L. CRE.	10501	L BLAIR	....
10677-10751	74	10677-10751	74	38	155.3	L.CRE/JURA	10501/10747	L BLAIR/ ROCK CK	/SS
10779-10805	26	10779-10785	6	3	135.7	JURASSIC	10747	ROCK CK	SS.
10817-10829	12	10819-10829	10	6	132.7	JURA.	10817	FERNIE	....
10833-10837	4	10833-10837	4	2	135.0	JURA.		FERNIE	....
10871-10887	16	10873-10885	12	6	159.0	JURA.	10857	NORDEGG	....
10917-10947	30	10917-10939	22	12	143.5	JURA.		NORDEGG	....
11065-11079	14	11071-11077	6	3	152.5	MISSISSIPP.	11034	SHUNDA	....
11109-11113	4	11109-11113	4	2	152.0	MISS.		SHUNDA	....
11307-11315	8	11309-11313	4	3	154.3	MISS.	11277	PEKISKO	....

ELONGATION ENDS 11315, PEKISKO; TOTAL DEPTH 11337,PEKISKO; D&A

WELL 16-16-52-21W5 15 ELONGATIONS 13 BREAKOUTS

12137-12187	50	12139-12187	48	25	136.8	U.DEVONIAN	12125	WABAMUN	DOL.
12293-12317	24	12293-12317	24	13	125.8	U. DEV.		WABAMUN	DOL/LST
12433-12531	98	12435-12529e	80	44	112.3	U. DEV.		WABAMUN	LST/DOL
12537-12571	34	12539-12571e	22	13	129.3	U. DEV.		WABAMUN	DOL.
12585-12611	26	12585-12609e	16	10	129.4	U. DEV.		WABAMUN	LST.
12623-12629	6	12625-12629	4	3	129.7	U.DEV.		WABAMUN	LST
12677-12657	20	12679-12691	12	7	139.6	U. DEV		WABAMUN	DOL.
12713-12725	12	12717-12725	8	5	121.8	U. DEV.		WABAMUN	DOL.
12861-12899	38	12861-12887e	16	5	134.0	U. DEV.	12843	BLUERIDGE	DOL/SH.
12977-12991	14	12979-12983	4	3	125.0	U. DEV.		BLUERIDGE	DOL.
13013-13071	58	13015-13059e	24	14	123.4	U. DEV.	13000/13015	CALMAR/NISKU	DOL,SH.
13259-13279	20	13259-13275e	10	7	124.1	U. DEV.	13015	NISKU	DOL/LST
13357-13381	24	13357-13381	24	13	123.8	U. DEV.	13308	LEDUC	DOL.

ELONGATION ENDS 13451, LEDUC; TOTAL DEPTH 13513 LEDUC(U.DEV) PROD. ZONE WABAMUN/ELKTON= /11274 (/MISS.)

WELL 10-27-45-16W5 20 ELONGATIONS 14 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC		INFORMATION	
12149-12503	354	12233-12495e	106	57	143.1	MISSISSIPP.	12109	PEKISKO	----
12527-12665	138	12565-12611	46	24	150.2	MISS.	12270	BANFF	-----
12759-13500	741	12789-13499e	314	157	137.0	/MISS/U.DEV.	/12777/12787	BANFF/EXSHAW/WABAMUN	----
13501-13865	364	13501-13861e	324	161	131.0	U. DEVONIAN	13502	NISKU	-----
13885-14103	218	13885-14095	210	106	132.8	U. DEV.	13502/14008	NISKU/IRETON	-----
14129-14151	22	14131-14145	14	7	130.4	U. DEV.	14008	IRETON	----
14153-14247	94	14153-14247	94	47	133.4	U. DEV.		IRETON	----
14263-14295	32	14275-14295	20	10	132.4	U DEV		IRETON	----
14301-14341	39	14313-14339	26	13	135.0	U. DEV		IRETON	----
14399-14431	32	14399-14423	24	14	131.7	U. DEV.		IRETON	----
14659-14669	10	14659-14669	10	5	143.0	U. DEV.	14659	DUVERNAY	----
14729-14841	112	14737-14835e	60	33	133.2	U. DEV.	14659/14788	DUV./B H L	----
14859-14901	42	14861-14869	8	4	143.0	U. DEV.	14788	BEAVERHILL LAKE	-----
15101-15407	306	15107-15399e	86	44	138.8	U. DEV.	/15162	B H L / SWAN HILLS	----

ELONGATION ENDS 15407,CAMBRIAN; TOTAL DEPTH 15448 CAMBRIAN=15245 D & A.

WELL 13-9-52-8W5 36 ELONGATIONS 20 BREAKOUTS

1526-1594	68	1540-1584	24	14	139.2				
1612-1620	8	1612-1620	8	3	144.7				
1626-2294	668	1638-2294e	422	104	145.9				
2398-2435	37	2398-2424e	9	3	125.7				
2440-2462	22	2456-2462	6	3	141.3				
2474-2550	76	2476-2532e	30	11	132.5				
2638-2670	32	2654-2666	12	6	132.8				
2754-2900	146	2770-2900e	122	26	128.2				
2906-2942	36	2908-2920	12	6	128.2				
2950-3140	190	2996-3094e	48	22	91.1				
3142-3200	58	44-50,72-89	23	7	45.1				
3294-3496	202	3412-3492e	70	24	175.7	U.CRETACEOUS	3413	LEA PARK	----
3569-3641	72	3616-3632	16	8	134.1	U. CRE.		LEA PARK	-----
3700-4376	676	3730-4342e	464	110	135.5	U. CRF	3413/3818/4317	LEA/1st WS/CARD ZONE	--/SH/--
6762-6864	102	6764-6864e	90	24	130.8	L CRE.	6762	D-1	----
6952-6976	24	6960-6972	12	6	125.0	L. CRE.		D-1	----
6980-7012	32	6988-6994	6	3	120.7	L. CRE.		D-1	----
7015-7042	27	7030-7042	12	4	128.8	L. CRE.		D-1	----
7082-7132	50	7086-7130	36	13	124.6	L. CRE.		D-1	----
7136-7194	58	7154-7194	40	10	125.5	L. CRE.		D-1	----

ELONGATION ENDS 7194, D-1; TOTAL DEPTH 8100,IRETON=7999;(U.DEV) PROD. ZONE NISKU =7854(U.DEV)

WELL 8-8N-51-9W5 m 11 ELONGATIONS 8 BREAKOUTS

2242-2255	13	2247-2249	2	2	145.5	U. DEVONIAN	2212.3m	WABAMUN	----
2256-2259	3	2256-2258	2	2	139.0	U. DEV.		WABAMUN	----
2287-2290	3	2287-2289	2	2	131.0	U. DEV.		WABAMUN	----
2296-2303	7	2296-2300	4	4	127.0	U. DEV.		WABAMUN	----
2343-2350	7	2344-2349	5	5	128.0	U. DEV.		WABAMUN	----
2431-2440	9	2431-2439	8	8	140.0	U. DEV.	2419.5m	BLUERIDGE	----
2442-2445	3	2442-2444	2	2	118.0	U. DEV.		BLUERIDGE	----
2446-2452	6	2446-2451	5	5	140.6	U. DEV.		BLUERIDGE	-----

ELONGATION ENDS 2451.5, BLUERIDGE. TOTAL DEPTH 2654m IRETON=2584m

WELL 6-20-50-15W5 46 ELONGATIONS 41 BREAKOUTS

9149-9161	12	9151-9159	8	4	143.0	JURA/MISS.	8972/9157	NORDEGG/SHUNDA	-----
9167-9171	4	9169-9171	2	1	134.5	MISSISSIPP.	9157	SHUNDA	-----
9173-9181	8	9173-9181	8	5	143.0	MISS.		SHUNDA	----
9195-9199	4	9195-9199	4	3	140.3	MISS.		SHUNDA	----
9201-9205	4	9201-9205	4	3	137.0	MISS.		SHUNDA	-----
9229-9233	4	9229-9233	4	3	123.3	MISS.		SHUNDA	-----
9237-9253	16	9237-9253	16	9	120.9	MISS.		SHUNDA	----
9267-9291	24	9267-9291	24	12	3.1	MISS.		SHUNDA	----
9297-9381	84	9297-9381	84	43	12.0	MISS.	9157/9330	SHUNDA/PEKISKO	----
9411-9417	6	9411-9413	2	1	124.0	MISS.	9330	PEKISKO	----

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC INFORMATION			
9427-9439	12	9433-9439	6	4	124.3	MISS.		PEKISKO	----
9439-9449	10	9441-9445	4	3	130.7	MISS.		PEKISKO	----
9469-9477	8	9469-9475	6	4	133.8	MISS.		PEKISKO	----
9503-9511	8	9503-9511	8	5	123.6	MISS.		PEKISKO	-----
9521-9539	18	9525-9539	14	6	123.6	MISS.		PEKISKO	-----
9681-9689	8	9681-9689	8	5	126.2	MISS.		PEKISKO	----
9693-9701	8	9693-9701	8	5	128.8	MISS.		PEKISKO	-----
10001-10010	9	10001-10005	4	2	129.0	U. DEVONIAN	10002	WABAMUN	-----
10021-10171	150	10023-10151	128	63	132.6	U. DEV.		WABAMUN	----
10221-10331	110	10223-10329	106	54	125.3	U. DEV.		WABAMUN	-----
10337-10345	8	10337-10345	8	5	132.6	U. DEV.		WABAMUN	-----
10347-10481	134	10347-10475	128	65	128.7	U. DEV.		WABAMUN	----
10485-10515	30	10485-10515	30	16	129.0	U.DEV.		WABAMUN	-----
10517-10531	14	10519-10531	12	7	124.6	U. DEV.		WABAMUN	-----
10533-10541	8	10533-10539	6	4	123.5	U. DEV.		WABAMUN	----
10543-10549	6	10545-10547	2	1	125.0	U. DEV.		WABAMUN	-----
10555-10575	20	10555-10559	4	4	120.5	U. DEV.		WABAMUN	-----
10613-10625	12	10613-10617	4	3	127.0	U. DEV		WABAMUN	----
10731-10771	40	33-41,45-51	14	9	124.8	U. DEV.		WINTERBURN,GRAMINIA	----
10775-10799	24	75-83,85-97	20	12	124.5	U.DEV.	10710	WINTERBURN,GRAMINIA	-----
10805-10849	44	10805-10843	38	19	120.7	U. DEV.	10710/10842	WINT,GRAM/CALMAR	----
10870-10923	53	10870-10916	46	28	120.7	U. DEV.	10868	NISKU	----
11167-11253	86	11170-11253	83	50	137.0	U. DEV.		NISKU	----
11332-11395	63	11332-11382	50	30	126.3	U. DEV.	11276	IRETON SH	SHALE
11590-11626	36	11596-11616	20	12	135.0	U. DEV.		IRETON SH	SHALE
11636-11646	10	11639-11642	3	2	126.0	U. DEV.		IRETON SH	SHALE
11652-11659	7	11652-11659	7	4	138.0	U. DEV.		IRETON SH	SHALE
11666-11682	16	11666-11682	16	10	134.0	U. DEV.		IRETON SH	SHALE
11689-11695	7	11682-11695	7	4	139.5	U. DEV.		IRETON SH	SHALE
11728-11735	7	11728-11735	7	4	135.0	U. DEV.		IRETON SH	SHALE
12035-12088	53	12048-12081e	23	14	141.0	U. DEV.	12019	BEAVERHILL LAKE	----

ELONGATION ENDS 12088, B H L; TOTAL DEPTH 12620, CAMBRIAN=12523   PROD. ZONE ROCK CK 8837(JURA)

WELL 3-36-49-23W5   143 ELONGATIONS   84 BREAKOUTS

1567-1723	156	1567-1687e	52	29	26.1
1735-2795	1060	1787-2791e	260	140	128.4
2796-2820	24	2799-2809	10	5	90.2
2850-2892	42	2863-2893	30	15	124.5
2909-3262	352	2909-3257e	228	121	158.7
3264-3297	33	3267-3279	12	7	3.1
3370-3466	96	3381-3411	30	15	161.5
3468-3488	20	3469-3485	16	6	155.3
3498-3598	100	3543-3549	6	3	136.0
3607-3679	72	3609-3645	36	18	144.4
3683-4113	430	3769-4103e	82	42	138.3
4129-4473	344	4189-4473e	54	30	11.7
4480-4505	25	4493-4505	12	6	176.0
4520-4532	12	4521-4529	8	5	88.0
4543-4570	27	4551-4569	18	10	178.4
4582-4633	51	4582-4633e	16	10	176.0
4643-4678	35	4643-4677	24	14	174.4
4707-4725	18	4707-4725	18	10	79.7
4810-4825	15	4811-4825	14	8	174.3
4828-4851	23	4829-4839	10	6	86.5
4886-6041	1155	4927-5989e	440	235	154.5
6133-6188	55	6145-6185e	36	20	169.1
6188-6319	131	6241-6251	10	6	125.7
6188-6319	0	6315-6319	4	3	33.0
6335-6566	231	6365-6565e	162	84	143.5

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC	INFORMATION		
6620-6730	110	6675-6685	10	5	172.5				
6620-6730	0	6685-6695	10	5	82.8				
6741-6825	84	6745-6809e	38	20	151.7				
6825-6850	25	6843-6849	6	4	157.8				
6858-6924	66	6858-6924	66	5	153.4				
6961-6979	18	6961-6967	6	3	142.6				
6983-7011	28	7001-7009	8	5	144.2				
7019-7189	170	7045-7167e	52	31	144.8	U.CRETACEOUS	7140	SOLOMON	SH/SS
7197-7280	83	7239-7279e	34	19	4.3	U. CRE.		SOLOMON	SH/SS
7399-7690	291	7399-7687e	126	69	158.6	U.CRE.	7140 / 7463	SOLOMON/WAPIABI	SH,SILTST,SS
7703-7712	9	7703-7707	4	3	124.0	U. CRE.	7463	WAPIABI	SILTST.
7713-7845	132	7717-7809e	56	30	15.4	U. CRE.		WAPIABI	SH/SILTST.
7847-7876	29	7847-7875	28	15	0.0	U. CRE.		WAPIABI	SH/SILTST.
7882-7921	39	7883-7889	6	4	6.5	U. CRE.		WAPIABI	SH/SILTST.
7939-8003	64	7939-7979	40	21	134.0	U. CRE.		WAPIABI	SILTST/SH
8009-8049	40	8011-8031e	12	8	138.5	U. CRE.		WAPIABI	SH/SILTST.
8063-8155	92	8129-8139	10	6	70.7	U. CRE.		WAPIABI	SH/SILTST.
8157-8511	354	8161-8511e	114	62	147.7	U. CRE.		WAPIABI/BADHEART (BADH)	SHALE
8523-8536	13	8525-8535	10	6	22.5	U. CRE.	/8495	BADHEART	SILTST/SH
8730-8928	208	8733-8763	30	15	140.4	U. CRE.		BADHEART	SILTST/SH
8730-8928	0	8773-8789	16	6	2 9	U. CRE.		BADHEART	SILTST/SH
8954-9200	246	8977-8983	6	3	131.0	U. CRE.	/8840/9019/9102	BADH/CARD ZN/ /	SILTST.
8954-9200	0	8993-9199e	18	9	6.0	U. CRE.	/8840/9019/9102	BADH/CARD ZN/CARD SD/BLKSTN	SS,SH
9433-9511	78	9441-9475	34	17	174.3	U. CRE.	9102	BLACKSTONE (BLKSTN)	SILTST/SH
9597-9675	78	9607-9659	52	26	175.2	U. CRE.		BLACKSTONE	SHALE
9761-9773	12	9761-9773	12	6	89.7	U. CRE.		BLACKSTONE	SHALE
9784-9845	61	9817-9839	22	12	175.6	U. CRE.		BLACKSTONE	SH/SILTST
9916-10027	111	9919-9925	6	5	30.5	U. CRE.		BLACKSTONE	SILTST/SH/SS
10135-10201	66	10161-10179	18	9	127.4	U. CRE.		BLACKSTONE	SH/SILTST/SS
10349-10549	200	10349-10515e	54	28	156.9	U. CRE.		BLACKSTONE	SILTST/SH/SS
10572-10849	277	10599-10849e	46	29	142.0	U. CRE.	9102/10740	BLKSTN/BFS	SILTST/SH/SS
10860-11069	209	10861-10867	6	4	137.0	L. CRE.	10860	MTN PARK	SS/SH
10860-11069	0	10869-10885	16	9	44.9	L. CRE.		MTN PARK	SS/SH
10860-11069	0	10949-10959	10	6	139.0	L. CRE.		MTN PARK	SS/SH
10860-11069	0	11049-11059	10	5	158.4	L. CRE.		MTN PARK	SH/SILTST
11122-11169	47	11123-11135	12	7	166.6	L. CRE.	11101	LUSCAR	SH/SILTST/COAL
12005-12051	46	12009-12023	14	7	135.0	L.CRE.	11420	BSE COAL	SS/SH/COAL
12057-12398	341	12059-12389e	170	85	158.0	L. CRE.		BSE COAL	SS/SH/SILT/COAL
12489-12786	297	12513-12783e	126	68	134.4	L.CRE/JURA	12460/12520/12690/	CADOMIN/NIK/U FERNIE/ROCK	SS,SH,SILT.
12813-12824	11	12815-12823	8	4	125.0	JURASSIC	12780	ROCK CK	SS
12880-12935	55	12909-12925	16	8	126.3	JURA.	/12905	ROCK CK/L FERNIE	SS,SH
13184-13452	268	13189-13433e	102	54	134.0	TRIASSIC	13130	TRI COQUINA	SH/DOL/SS
13454-13500	46	13475-13489e	8	4	150.0	MISSISSIPPIAN	13350	TURNER VALLEY (TV)	DOL/SS
13722-13745	23	13725-13729	4	3	121.3	MISS.	13685	2nd TV	DOL/SS
13838-13847	9	13841-13845	4	2	104.5	MISS.		2nd TV	DOL.
13877-13890	13	13877-13887e	6	3	148.3	MISS.		2nd TV	DOL/SH
14091-14104	13	14093-14101	8	4	140.0	MISS.	14085	PEKISKO	LST.
14155-14233	78	14159-14233e	32	17	134.9	MISS.	/14220	PEKISKO/BANFF	LST,DOL,ANHY,SS
14273-15511	1238	14529-14599e	56	28	12.5	MISS./U.DEVONIAN	/14727/15500	BANFF/WAB./WINT.	LST,SH,DOL
15514-15534	20	15515-15523	6	4	140.0	U.DEV.	/15532	WINT./NISKU EQUIV	SH,LST,SS
15579-15592	13	15583-15587	4	2	142.0	U.DEV.		NISKU EQUIV.	DOL/ANHY
15817-15966	149	15829-15835	6	4	133.5	U.DEV.		NISKU EQUIV.	DOL.
16832-17150	318	16851-17097e	72	37	126.9	U. DEV.	16190/16925	D-3/B H L	DOL,LST
17235-17325	90	17263-17321e	30	17	143.6	CAMBRIAN	17230	CAMBRIAN	DOL.
17375-17382	7	17375-17381	6	3	150.7	CAM.		CAMBRIAN	SS.
17422-17469	47	17431-17441	10	5	146.2	CAM.		CAMBRIAN	DOL.
17472-17485	13	17477-17483	6	3	151.7	CAM.N		CAMBRIAN	DOL/SS
17631-17795	164	17635-17685e	20	10	164.3	CAM.		CAMBRIAN	LST/SH
17960-17999	39	17961-17997	36	18	135.3	CAM.		CAMBRIAN	SH.

ELONGATION ENDS 17999, CAMBRIAN; TOTAL DEPTH 18300, CAMBRIAN

PROD. ZONE TURNER VALLEY.(MISS)

WELL 5-9-51-9W5   4 ELONGATIONS   2 BREAKOUTS

6750-7550	800	6767-7395e	216	113	144.6
7562-8024	462	7569-7906e	124	65	153.4

ELONGATION ENDS 8024, ;TOTAL DEPTH 8649, IRETON=8488   PROD. ZONE NISKU=8148.

WELL 5-33-109-8W6   5 ELONGATIONS   3 BREAKOUTS

5214-5332	118	5216-5332e	110	55	97.9
5349-5400	51	5354-5382	30	15	174.3
5540-5570	30	5546-5564	20	10	121.6

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC INFORMATION
WELL 7-18RN-109-7W6		12 ELONGATIONS	9 BREAKOUTS			
4912-4922	10	4912-4920	10	5	15.5	
5040-5074	34	5044-5072	30	15	172.0	
5516-5562	46	5522-5552e	40	20	16.0	
5604-5614	10	5604-5612	10	5	12.6	
5628-5638	10	5628-5636	10	5	11.2	
5740-5750	10	5740-5748	10	5	27.6	
5780-5790	10	5780-5788	10	5	13.4	
5800-5810	10	5800-5808	10	5	25.7	
5850-5886	36	5864-5872	10	5	35.4	
WELL 10-17RN-110-9W6		11 ELONGATIONS	5 BREAKOUTS			
4140-4288	148	4142-4280	140	70	41.7	
4290-4358	68	4298-4356	60	30	58.0	
4368-4410	42	4374-4402	30	15	88.0	
4452-4564	112	4466-4564	100	50	56.0	
5656-5700	44	5656-5684	30	15	164.0	
WELL 2-20-81-9W5		7 ELONGATIONS	5 BREAKOUTS			
4084-4210	126	4084-4192	110	55	117.8	
4224-4264	40	4224-4262	40	20	118.9	
4266-4384	118	4268-4376	110	55	114.6	
4414-4564	150	4494-4552	60	30	111.3	
WELL 4-15-81-9W5		7 ELONGATIONS	3 BREAKOUTS			
4908-4982	74	4912-4970	20	10	117.1	
5054-5098	44	5056-5074	20	10	125.9	
5122-5208	86	5140-5168	30	15	112.0	
WELL 5-3-81-9W5		20 ELONGATIONS	9 BREAKOUTS			
3316-3348	32	3320-3338	20	10	61.6	
4062-4172	110	4062-4150	90	45	103.1	
4208-4218	10	4208-4216	10	5	159.5	
4224-4478	254	4302-4476	100	50	98.0	
4490-5126	636	4856-5098	240	120	98.4	
5378-5472	94	5378-5456	80	40	97.5	
5478-5510	32	5488-5496	10	5	94.1	
5530-5600	70	5530-5578	50	25	92.8	
5628-5654	26	5628-5646	20	10	93.7	
WELL 4-20-81-9W5		28 ELONGATIONS	17 BREAKOUTS			
654-1022	368	786-984	200	100	116.0	
1094-1116	22	1094-1112	20	10	143.8	
1126-1150	24	1126-1144	20	10	15.5	
1232-1282	50	1244-1282	40	20	132.0	
1310-1628	318	1350-1602	250	125	121.8	
1682-1694	12	1682-1690	10	5	116.0	
4144-4154	10	4144-4152	10	5	114.2	
4156-4166	10	4156-4164	10	5	120.7	
4188-4234	46	4190-4208	20	10	114.7	
4270-4296	26	4270-4278	10	5	103.7	
4308-4450	142	4308-4436	130	65	117.5	
4466-4606	140	4546-4594	50	25	124.0	
4738-4758	20	4738-4756	20	10	60.8	
4776-4814	38	4780-4798	20	10	71.9	
4878-4982	104	4882-4980	100	50	138.4	
4982-5006	24	4984-5002	20	10	146.4	
5008-5068	60	5008-5066	60	30	152.7	
WELL 14-9-118-8W6		27 ELONGATIONS	4 BREAKOUTS			
942-1044	102	994-1042	50	25	147.2	
1138-1450	312	1406-1444	40	20	105.4	
2260-2286	26	2260-2278	20	10	169.3	
2568-2608	40	2572-2608e	30	15	153.5	

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC		INFORMATION	
WELL 2-36-118-8W6	10 ELONGATIONS	4 BREAKOUTS							
4884-4934	50	4884-4922	40	20	142.3				
4964-4978	14	4964-4972	10	5	60.1				
5198-5268	70	5214-5262	50	25	146.4				
5410-5482	72	5422-5468	40	20	166.1				
WELL 9-15-118-8W6	8 ELONGATIONS	3 BREAKOUTS							
5164-5286	122	5178-5280e	90	45	128.2				
5356-5386	30	5356-5374	20	10	133.0				
5446-5468	22	5448-5466	20	10	126.2				
WELL A9-5-82-9W5	4 ELONGATIONS	3 BREAKOUTS							
5142-5170	28	5148-5166	20	10	76.2				
5206-5222	16	5206-5214	10	5	63.3				
5272-5298	26	5272-5280	10	5	51.2				
WELL 14-21-81-9W5	14 ELONGATIONS	1 BREAKOUT							
5680-5820	140	5680-5782e	80	40	120.9				
WELL 10-9-81-9W5	11 ELONGATIONS	1 BREAKOUT							
5560-5608	48	5560-5598	40	20	123.4				
WELL 3-21-112-6W6	6 ELONGATIONS	2 BREAKOUTS							
4384-4414	30	4386-4412	30	15	160.0	----	----	-----	SH/LST.
4650-4664	14	4654-4662	10	5	154.0	---	----	-----	DOL/LST
ELONGATION ENDS******,	TOYAL DEPTH 5430, KEG RIVER Fm.								
WELL 3-1-119-9W6	18 ELONGATIONS	4 BREAKOUTS							
924-1800	876	1540-1578	40	20	155.0				
4700-4782	82	4700-4768	70	35	133.1				
5166-5290	124	5186-5214	30	15	54.7				
5728-5752	24	5728-5746	20	10	148.7				
WELL 13-35-112-10W6	22 ELONGATIONS	13 BREAKOUTS							
4400-4640	240	4522-4560	40	20	85.0				
4658-4668	10	4658-4666	10	5	144.9				
4844-4884	40	4844-4872	30	15	154.7				
4980-5036	54	5016-5034	20	10	117.7				
5088-5146	58	5088-5136	50	25	164.8				
5190-5300	110	5206-5264	60	30	150.6				
5316-5364	48	5318-5356	40	20	154.4				
5372-5386	14	5372-5380	10	5	158.9				
5524-5542	18	5532-5540	10	5	158.6				
5590-5600	10	5590-5598	10	5	178.5				
5680-5722	42	5680-5718	40	20	162.0				
5750-5774	24	5750-5768	20	10	137.0				
5886-5912	26	5886-5904	20	10	145.2				
WELL 12-33-116-6W6	38 ELONGATIONS	6 BREAKOUTS							
790- 954	164	902-950	50	25	139.2				
4264-4286	22	4268-4276	10	5	48.4				
4374-4388	14	4374-4388	10	5	121.7				
4500-4520	20	4500-4518	20	10	139.3				
4620-4630	10	4620-4628	10	5	19.5				
4728-4796	68	4750-4788	40	20	56.0				
4856-4868	12	4856-4864	10	5	146.6				
4950-5020	70	4950-4978	30	15	144.3				
WELL 12-33-114-5W6	1 ELONGATIONS	1 BREAKOUT							
4770-4910	140	4777-4905	120	60	119.8				

WELL 14-36-116-6W6 4 ELONGATIONS 3 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC	INFORMATION		
4408-4418	10	4408-4416	10	5	96.3				
4750-4770	20	4750-4758	10	5	81.5				
4796-4882	86	4796-4854	60	30	28.0				

WELL 3-11-121-7W6 4 ELONGATIONS 2 BREAKOUTS

4860-4872	12	4860-4868	10	5	161.2				
5304-5350	46	5304-5322	20	10	158.0				

WELL 12-24-82-6W6 19 ELONGATIONS 10 BREAKOUTS

4864-4908	44	4864-4882	20	10	80.1	MISSISSIPP.	4812	DEBOLT	LST.
4912-5034	122	4918-5026	110	55	76.8	MISS.		DEBOLT	LST/DOL.
5038-5150	112	5046-5134	90	45	119.5	MISS.		DEBOLT	LST/DOL/ANHY/SILT
5256-5296	40	5256-5294	40	20	114.0	MISS.		DEBOLT	LST/SH
5312-5342	30	5316-5334	20	10	78.5	MISS.		DEBOLT	LST/SILTST.
5362-5570	208	5372-5528e	100	50	114.8	MISS.	/5518	DEBOLT/ELKTON	LST,SH,DOL
5670-5700	30	5670-7698	30	15	102.6	MISS.	5643	SHUNDA	SH/ LST.
5700-5734	34	5700-5728	30	15	100.0	MISS.		SHUNDA	LST.
5756-6190	434	5760-6178	380	190	110.2	MISS.	/6174	SHUNDA/BANFF	LST,SH,DOL
6310-6446	136	6338-6446e	90	45	109.5	MISS.	6174	BANFF	LST/SH/ANHY/SILTS

ELONGATION ENDS 6958, WABAMUN (DEVONIAN)=6838 , TOTAL DEPTH 7085, PRECAMBRIAN=6985 D&A.

WELL 11-29-82-5W6 31 ELONGATIONS 19 BREAKOUTS

4300-4320	20	4300-4308	10	5	96.5	TRIASSIC	3530	TOAD GRAYLING	SS.
4334-4374	40	4350-4368	20	10	107.3	TRI/PERMIAN	/4367	TOAD GRAYLING/BELLOY	SILTST,SS,DOL
4446-4456	10	4446-4454	10	5	72.0	PERMIAN	4367	BELLOY	SS/DOL
4528-4542	14	4528-4536	10	5	104.6	PERM.		BELLOY	SS/SH/DOL
4880-4904	24	4880-4898	20	10	63.9	MISSISSIPP.	4774	DEBOLT	LST.
5002-5056	54	5002-5050	50	25	76.8	MISS.		DEBOLT	LST/DOL
5062-5112	50	5092-5'10	20	10	86.8	MISS.		DEBOLT	LST/SH/DOL
5400-5448	48	5408-5436	30	15	114.7	MISS.		DEBOLT	LST/SH
5482-5528	46	5482-5520	40	20	111.6	MISS.	/5488	DEBOLT/ELKTON	LST/SH
5724-5758	34	5724-5752	30	15	120.0	MISS.	5617	SHUNDA	SH/LST/DOL.
5898-5930	32	5898-5926	30	15	117.3	MISS.		SHUNDA	LST/SH
6010-6040	30	6010-6038	30	15	45.3	MISS.	5940	PEKISKO	LST/SH
6042-6062	20	6042-6050	10	5	126.8	MISS.		PEKISKO	SH
6160-6212	52	6160-6208	40	20	101.4	MISS.	/6181	PEK/BANFF	SH,LST, SILTST.
6246-6310	64	6246-6304	60	30	128.0	MISS.	6181	BANFF	SILTS/SH.
6368-6410	42	6368-6396	30	15	105.3	MISS.		BANFF	LST/SILTST/SH
6412-6444	32	6420-6430	10	5	116.6	MISS.		BANFF	LST
6456-6554	98	6466-6544	80	40	106.0	MISS.		BANFF	LST/SH

ELONGATION ENDS 7058 WABAMUN (DEVONIAN)=6980; TOTAL DEPTH 7315 PRECAMBRIAN=7283; PROD ZONE WABAMUM/BANFF/DEBOLT.

WELL 15-29-115-3W6 29 ELONGATIONS 12 BREAKOUTS

1590-1648	58	1604-1622	20	10	121.0				
1762-1820	58	1780-1818	40	20	157.0				
1832-1900	68	1832-1880	50	25	166.3				
1932-1968	36	1932-1960	30	15	137.3				
1968-2064	96	1980-2058e	40	20	178.2				
2090-2196	106	2090-2178	90	45	5.3				
2240-2354	114	2242-2330	90	45	8.0				
3310-3500	190	3310-3498	190	95	8.6				
3500-3600	100	3500-3598	100	50	14.8				
3692-3716	24	3696-3714	20	10	117.6				
3810-3840	30	3814-3822	10	5	120.9				
4214-4230	16	4218-4226	10	5	157.5				

WELL 5-28-115-4W6 5 ELONGATIONS 3 BREAKOUTS

4430-4472	42	4430-4462	30	15	157.5	DEVONIAN	4252	MUSKEG	ANHY/DOL.
4508-4534	26	4510-4518	10	5	162.6	DEVONIAN		MUSKEG	ANHYDRITE
4632-4664	28	4644-4662	20	10	144.5	DEVONIAN		MUSKEG	ANHY/DOL/

ELONGATION ENDS 4778, KEG RIVER (DEVONIAN)=****,TOTAL DEPTH 5210
LOWER ELK POINT (DEVONIAN)=5184

WELL 5-5-35-11W5 33 ELONGATIONS 12 BREAKOUTS

ELONGATED INTERVALS		BREAKOUT INTERVALS				STRATIGRAPHIC INFORMATION		
14436-14454	18	14441-14449	10	5	47.2			
14462-14474	12	14463-14471	10	5	34.3			
14476-14496	20	14477-14485	10	5	31.9			
14644-14670	26	14659-14666	10	5	132.6			
14702-14784	82	14703-14777e	60	30	157.3			
14850-14984	134	14853-14961	110	55	145.1			
14984-15004	20	14993-15001	10	5	90.4			
15086-15105	22	15089-15097	10	5	132.7			
15940-16096	156	15941-16089	150	75	176.6			
16096-16600	504	16151-16589	440	220	175.6			
16600-16748	148	16603-16711	100	50	0.6			
16802-16868	66	16811-16829	20	10	147.5			

WELL 7-7-86-1W6 30 ELONGATIONS 4 BREAKOUTS

5578-5600	20	5579-5597	20	10	125.8	MISSISSIPP 4966	BANFF	DOL/LST.
5608-5632	24	5609-5617	10	5	142.3	MISS.	BANFF	LST/SH
5804-5842	38	5805-5833	30	15	100.0	MISS/U.DEV /5838	BANFF/WABAMUN	LST.
6506-6624	118	6511-6641	112	56	116.6	U.DEVONIAN 6502	IRETON	LST/DOL.

ELONGATION ENDS 6624 IRETON; TOTAL DEPTH 7214 PRECAMBRIAN=7193;D&A

WELL 9-18-83-6W6 12 ELONGATIONS 10 BREAKOUTS

5128-5138	10	5128-5136	10	5	142.3
5640-5670	30	5646-5664	10	5	103.1
5812-6616	354	5812-6160	350	175	117.0
6178-6200	22	6178-6196	20	10	113.3
6450-6594	144	6450-6588	140	70	114.4
6646-6782	136	6646-6774	130	65	112.0
7252-7288	36	7260-7268	10	5	152.4
7380-7410	30	7386-7394	10	5	37.1
7504-7528	24	7504-7512	10	5	125.7
7558-7570	12	7560-7568	10	5	111.2

WELL 14-21-37-11W5 38 ELONGATIONS 30 BREAKOUTS

7260-7700	440	7280-7388e	370	185	148.1	U.CRETACEOUS 5708/7318	MAIN FAULT/BEARPAW	SS,SILT,SH
7800-8162	362	7802-8160	360	180	144.0	U.CRE. 7598	BELLY RIVER	SS/SH.
8430-8490	60	8432-8490	60	30	142.7	U. CRE.	BELLY RIVER	SS/SH
8564-8622	58	8570-8618	50	25	163.2	U. CRE.	BELLY RIVER	SS/SH
8754-8854	100	8754-8852	100	50	156.4	U. CRE.	BELLY RIVER	SS/SH
8976-8990	14	8976-8984	10	5	85.5	U. CRE.	BELLY RIVER	SS
8990-9038	48	9028-9036	10	5	156.6	U. CRE.	BELLY RIVER	SS/SH
9078-9142	64	9084-9132	50	25	156.0	U. CRE.	BELLY RIVER	SS
9206-9534	328	9316-9530e	160	80	152.9	U. CRE.	BELLY RIVER	SS/SH.
9594-10182	588	9622-10180	560	280	155.4	U. CRE.	BELLY RIVER	SH/SILTST/SS
10194-10240	46	10194-10212	20	10	100.3	U. CRE.	BELLY RIVER	SILTST.
10248-10316	68	10284-10312	30	15	117.3	U. CRE.	BELLY RIVER	SH/SS
10318-10826	508	10330-10768	440	220	153.0	U. CRE.	BELLY RIVER	SH /SILTST.
10836-10904	68	10864-10882	20	10	154.0	U. CRE. 10826	CARDIUM	SH/SS.
10932-10952	20	10940-10948	10	5	157.7	U. CRE.	CARDIUM	SH/SS
10958-11294	336	10960-11278	320	160	147.9	U. CRE.	CARDIUM	SH/SILTST/SS
11340-11440	100	11346-11424	80	40	159.5	U. CRE.	CARDIUM	SS/SH.
11456-11550	94	11460-11488	30	15	164.0	U. CRE.	CARDIUM	SH
11550-11640	90	11552-11630	80	40	162.0	U CRE.	CARDIUM	SH/SS
11650-11700	50	11658-11696	40	20	161.0	U. CRE.	CARDIUM	SH
11700-11858	158	11700-11838	140	70	161.7	U. CRE.	CARDIUM	SH/SILTST/SS
11894-12030	136	11906-12012e	90	45	158.2	L. CRE. /11994	CARD / BFS	SH,SS.
13138-13200	62	13170-13208	40	20	143.0	JURASSIC 13100/13177	FERNIE/ROCK CK	SS.
15826-16134	308	15850-16118	270	135	146.5	U.DEVONIAN 15575	IRETON	SH/GYP/MARLST.
16244-16290	46	16250-16278	30	15	149.3	U. DEV. 16146/16252	DUVERNAY/B H L	LST,SH
16352-16414	62	16356-16404	50	25	148.0	U. DEV. 16252	BEAVERHILL LAKE	LST/SH
16460-16594	134	16462-16580	120	60	149.0	U. DEV.	B H L	LST/SH
16634-16662	28	16636-16654	20	10	140.4	U.DEV.	B H L	LST.
16744-16826	82	16744-16812	70	35	147.5	U. DEV. /16748	B H L/SLAVE POINT	DOL.
16842-16902	60	16846-16894	50	25	141.6	U. DEV.	SLAVE POINT	DOL/LST.

ELONGATION ENDS 16902, SLAVE POINT; TOTAL DEPTH 16980, 2nd H= (MID. DEV.)

WELL 2-29-59-22W5 72 ELONGATIONS 41 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC		INFORMATION	
7700-7804	104	7702-7796	80	40	108.5	L.CRETACEOUS	7674/7725/7752	VIKING/JOLI F/MANNVILLE	SS,SH,SILTST.
7806-7820	14	7810-7818	10	5	86.4	L. CRE.	7752	MANNVILLE	SS/SH
7840-8004	164	7862-8000	140	70	164.3	L. CRE.		MANNVILLE	SS/SILTST/SH
8130-8176	44	8132-8170	40	20	73.0	L. CRE.		MANNVILLE	SILT/SS/SH/COAL
8186-8340	154	8190-8328	140	70	134.3	L. CRE.		MANNVILLE	SS/SILT/COAL/SH
8366-8496	130	8370-8478	110	55	120.7	L. CRE.		MANNVILLE	SH/SS/SILTST.
8542-8584	42	8546-8574	30	15	142.7	L. CRE.		MANNVILLE	SH/SS/SSILTST.
8600-8634	34	8600-8618	20	10	5.3	L. CRE.	/8603	MANNV/L MANNVILLE	SH,SS,SILTST.
8672-8684	10	8672-8680	10	5	125.2	L. CRE.	8603	LOWER MANNVILLE	SS/SILTST.
8714-8730	16	8718-8726	10	5	129.4	L. CRE.		L MANNVILLE	SS/SILTST.
8764-8776	12	8764-8772	10	5	139.3	L. CRE.		L MANNVILLE	SS/COAL/SH
8796-8818	22	8796-8804	10	5	137.7	L. CRE.		L MANNVILLE	SS/SH/SILTST.
8826-8838	10	8826-8834	10	5	148.1	L. CRE.		L MANNVILLE	SH/SILTST.
8912-8972	60	8912-8970	60	30	130.0	L. CRE.		L MANNVILLE	SS/SILTST/SH
9398-9488	90	9424-9484	40	20	130.0	CRE/MISS	/9420	L MANNV/DEBOLT	DOL/SILT/SS.
9496-9516	20	9500-9508	10	5	109.0	MISS.	9420	DEBOLT	DOL/SH
9590-9618	28	9602-9610	10	5	134.8	MISS.	9517	ELKTON	DOL.
9622-9638	16	9622-9630	10	5	142.7	MISS.	/9635	ELKTON/SHUNDA	LST,DOL,SH
9686-9708	22	9696-9704	10	5	146.2	MISS.	9635	SHUNDA	DOL/LST/SH
9756-9806	50	9756-9794	40	20	133.0	MISS.		SHUNDA	LST/DOL/SH
10012-10028	16	10012-10020	10	5	54.2	MISS.	10010	BANFF	SH/SILTST/SS
10050-10096	46	10056-10094	40	20	55.0	MISS.		BANFF	DOL/SILT/SH
10124-10154	30	10128-10146	20	10	93.0	MISS.		BANFF	SILTST/SH
10162-10178	16	10162-10170	10	5	141.1	MISS.		BANFF	SILTST/DOL
10196-10230	34	10198-10216	20	10	118.8	MISS.		BANFF	SH/SS/LST
10270-10282	12	10272-10280	10	5	107.0	MISS.		BANFF	LST.
10340-10392	52	10340-10378	40	20	73.0	MISS.		BANFF	SH/LST/SILTST.
10590-10604	14	10592-10600	10	5	146.8	MISS.		BANFF	LST/SILTST.
10648-10972	324	10648-10966	320	160	140.1	U.DEVONIAN	10620	WABAMUN	LST/DOL.
10984-11214	230	10986-11204	220	110	139.5	U. DEV.		WABAMUN	LST/DOL.
11218-11404	166	11228-11378	150	75	136.3	U. DEV.	/11362	WABAMUN/WINTERBURN	LST/DOL.
11444-11482	38	11444-11472	30	15	130.7	U. DEV.	11362	WINTERBURN	DOL
11490-11516	26	11494-11512	20	10	155.5	U. DEV.	11490	NISKU	LST.
11532-11542	10	11532-11540	10	5	124.3	U. DEV.		NISKU	LST
11552-11572	20	11552-11570	20	10	121.5	U. DEV.		NISKU	LST.
11888-11900	12	11890-11898	10	5	168.4	U. DEV.	11810	IRETON	ANHYDRITE
12600-12612	12	12600-12608	10	5	156.4	U. DEV.	12379	LEDUC	DOL.
12656-12746	88	12658-12736	80	40	138.0	U. DEV.	/12667	LEDUC/B H L	LST/DOL.
12794-12826	32	12796-12824	30	15	144.3	U. DEV.	12667	BEAVERHILL LAKE	LST/DOL
12836-12850	14	12838-12846	10	5	144.5	U. DEV.		B H L	LST/DOL
12854-12864	10	12854-12862	10	5	132.9	U. DEV		B H L	LST

ELONGATION ENDS 12864, B H L; TOTAL DEPTH 12865, B H L;
PROD. ZONE LOWER MANNVILLE.

WELL 10-7-60-14W5 16 ELONGATIONS 11 BREAKOUTS

7452-7464	12	7454-7462	10	5	115.5
7558-7600	42	7558-7586	30	15	24.5
7634-7664	30	7634-7662	30	15	156.0
7672-7722	50	7686-7714	30	15	133.3
8034-8054	20	8034-8052	20	10	159.1
8096-8184	88	8098-8176	80	40	150.5
8260-8272	12	8260-8268	10	5	165.0
8284-8374	90	8284-8362	80	40	162.0
8520-8560	40	8522-8550	30	15	141.3
8572-8584	12	8574-8582	10	5	150.7
8650-8660	10	8650-8658	10	5	149.2

WELL 3-32-34-8W5 15 ELONGATIONS 9 BREAKOUTS

STRATIGRAPHIC INFORMATION

ELONGATED	INTERVALS	BREAKOUT	INTERVALS		
4558-5112	554	4560-4618	58	29	123.0
4558-5112	0	4640-4858	218	109	155.0
4558-5112	0	4860-4918	58	29	165.0
4558-5112	0	4920-5078	158	79	154.0
4558-5112	0	5080-5112	32	16	129.0
6074-6518	444	6078-6518	440	220	133.0
6636-6788	152	6636-6708	72	36	133.0
6636-6788	0	6720-6750	30	15	135.0
6636-6788	0	6760-6788	28	14	135.0
6796-6940	144	6796-6940	144	72	133.0
6950-7150	100	7100-7148	48	24	168.0
7164-7400	236	7190-7368	178	89	116.0
7470-7876	406	7766-7806	40	20	142.0
7946-8722	780	8078-8120	42	21	162.0
7946-8722	0	8122-8282	160	80	142.0
7946-8722	0	8282-8300	18	9	134.0
7946-8722	0	8510-8716	206	103	130.0
8900-9012	112	8902-9000	98	49	127.0

WELL 6-17-37-9W5 41 ELONGATIONS 39 BREAKOUTS

7106-7138	32	7106-7138	32	16	126.0
7154-7180	26	7156-7176	20	10	126.0
7280-7316	36	7280-7316	36	18	128.0
7326-7336	10	7326-7336	10	5	123.0
7346-7356	10	7346-7352	6	3	119.0
7364-7396	32	7364-7394	30	15	125.0
7440-7520	80	7444-7520	76	38	125.0
7526-7566	40	7530-7566	36	18	119.0
7576-7590	14	7576-7590	14	7	118.0
7594-7662	68	7602-7658	56	28	128.0
7694-7714	20	7694-7714	20	10	135.0
7728-7744	20	7732-7744	12	6	120.0
7764-7774	10	7766-7774	8	4	121.0
7904-7942	38	7904-7942	38	19	120.0
7946-8060	114	7946-8060	114	57	117.0
8078-8086	8	8080-8086	6	3	122.0
8136-8164	28	8136-8164	28	14	125.0
8196-8222	26	8196-8212	16	8	127.0
8260-8280	20	8260-8280	20	10	123.0
8300-8370	70	8310-8370	60	30	115.0
8380-8400	20	8380-8398	18	9	120.0
8410-8424	14	8414-8424	10	5	121.0
8440-8476	36	8442-8474	32	16	114.0
8540-8550	10	8540-8550	10	5	130.0
8636-8660	24	8636-8660	24	12	125.0
8760-8776	16	8764-8776	12	6	127.0
8786-8870	84	8786-8866	80	40	130.0
8884-8914	30	8888-8914	26	13	114.0
8948-8966	18	8948-8964	16	8	117.0
8990-9006	16	8990-9006	16	8	116.0
9026-9032	6	9026-9032	6	3	112.0
9034-9212	178	9034-9212	178	89	115.0
9260-9400	140	9260-9398	138	69	126.0
9502-9526	24	9502-9526	24	12	133.0
9560-9622	62	9560-9622	62	31	124.0
9676-9882	206	9676-9878	202	101	117.0
9926-10058	132	9930-10058	128	64	120.0
10086-10194	108	10100-10140	40	20	122.0
10086-10194	0	10160-10194	34	17	135.0
10212-10258	46	10214-10250	36	18	119.0

WELL A2-13-34-11W5   9 ELONGATIONS   7 BREAKOUTS

ELONGATED	INTERVALS	BREAKOUT	INTERVALS			STRATIGRAPHIC		INFORMATION	
12940-12958	18	12940-12952	12	6	140.0	MISSISSIPP.	12771	BELLOY	LST/SH
12964-13010	46	12968-13010	42	21	135.0	MISS.		BELLOY	LST/SH
13300-13340	40	13302-13336	34	17	130.0	MISS.		BELLOY	LST/SH
13560-13582	22	13560-13568	8	4	169.0	MISS.	13552	PEKISKO	DOL/LST/ANHY
13560-13582	0	13574-13582	8	4	126.0	MISS.		PEKISKO	SHALE
13700-13740	40	13714-13728	14	7	172.0	MISS.		PEKISKO	LST/SH
13836-13842	6	13836-13840	4	2	122.0	MISS.		PEKISKO	DOL/ANHY
15348-15358	10	15350-15356	6	3	136.0	U.DEVONIAN	15343	CALMAR	DOL/ANHY

ELONGATION ENDS 15358, CALMAR; TOTAL DEPTH 15497

WELL 7-17-33-7W5   31 ELONGATIONS   17 BREAKOUTS

1586-1716	130	1610-1706	96	48	8.0
1788-1860	72	1798-1850	52	26	60.0
2120-2220	100	2120-2144	24	12	128.0
2120-2220	0	2146-2220	74	37	148.0
2636-2666	30	2636-2666	30	15	132.0
2700-2808	108	2702-2808	106	53	66.0
2814-2850	36	2814-2846	32	16	74.0
2850-2880	30	2856-2876	20	10	81.0
2880-3320	440	2880-2908	28	14	122.0
2880-3320	0	2932-3000	68	34	128.0
2880-3320	0	3002-3062	60	30	98.0
3320-3966	646	3320-3410	90	45	129.0
3320-3966	0	3440-3500	60	30	167.0
3320-3966	0	3840-3966	126	63	28.0
4770-5028	258	4802-4828	26	13	160.0
4770-5028	0	4920-5026	106	53	149.0
5310-5430	120	5376-5420	44	22	130.0
5434-6112	678	5450-5628	178	89	140.0
5434-6112	0	5654-5704	50	25	4.0
5434-6112	0	5716-5758	42	21	6.0
5434-6112	0	5902-6108	206	103	146.0
6150-6388	238	6152-6192	40	20	114.0
6150-6388	0	6228-6382	154	77	142.0
6924-7250	326	6940-7000	60	30	122.0
6924-7250	0	7002-7042	40	20	133.0
6924-7250	0	7044-7070	26	13	141.0
6924-7250	0	7072-7136	64	32	158.0
6924-7250	0	7200-7240	40	20	147.0
7310-7510	200	7310-7484	174	87	142.0
7740-7770	30	7742-7768	26	13	143.0
8054-8070	16	8054-8062	8	4	137.0

BIMODAL WELLS.

WELL 15-9-116-6W6   2 ELONGATIONS   2 BREAKOUTS

4316-4328	12	4316-4326	10	5	86.2
4408-4474	66	4408-4438	30	15	172.2

WELL 3-1-116-1W6   2 ELONGATIONS   2 BREAKOUTS

4962-4974	12	4962-4972	10	5	146.4
5122-5142	20	5126-5136	10	5	65.3

TABLE 3.2

Statistics of breakout azimuths for wells listed in Table 3.1
(All lengths are in feet except where indicated)

WELL	LOGGED	ELONGATIONS	LENGTH	BREAKOUTS	LENGTH	N	MEAN AZIMUTH(DEG)	S.D(DEG)	S.E(DEG)
6-30-46-17W5	3226-12106	80	7148	51	3080	1540	145.9	10.8	0.3
7-9-49-24W5	1418-13939	144	9357	71	2336	1168	156.7	21.3	0.6
12-19-53-8W5	6350-7827	11	420	10	262	131	123.8	2.4	0.2
b-45-A-94-P-14	5650-6089	13	103	6	32	16	60.9	17.1	4.6
6-12-50-11W5 m	461-2874.5m	18	249	12	87	46	126.3	2.9	0.4
14-20-50-12W5	1230-9558	28	831	24	418	209	122.4	4.7	0.3
4-26-51-11W5	8484-9123	2	56	2	52	26	119.8	3.3	0.7
3-32-47-13W5	9566-11494	28	758	23	526	263	131.3	7.6	0.5
6-30-48-12W5	10011-11630	13	316	12	242	121	133.9	4.1	0.4
10-25-45-15W5	10450-11335	13	298	11	204	102	148.3	3.8	0.4
16-16-52-21W5	9000-13452	15	514	13	292	146	124.9	4.6	0.4
10-27-45-16W5	13500-15407	20	2624	14	1342	671	135.3	2.3	0.1
13-9-52-8W5	1526-7420	36	3098	20	1462	730	137.4	7.5	0.3
8-8N-51-9W5 m	2200-2451.5m	11	78	8	30	16	134.7	3.8	1.0
6-20-50-15W5	-----	46	1330	41	976	491	132.5	9.1	0.4
3-36-49-23W5	1507-18002	143	14518	84	3344	1672	151.2	10.6	0.3
5-9-51-9W5	5550-8024	4	2455	2	340	170	147.8	2.1	0.2
10-7-60-14W5	7500-8736	16	450	11	340	170	154.3	8.8	0.7
2-29-59-22W5	7700-12864	72	2717	41	1880	940	135.0	10.4	0.3
14-21-37-11W5	5084-12040e	37	5016	30	3060	1530	151.0	4.7	0.1
7-7-86-1W6	795-7213	30	2453	4	190	95	114.3	3.4	0.4
9-18-83-6W6	5000-7675	12	876	10	710	355	115.4	4.5	0.2
5-5-35-11W5	14205-18000	33	1560	12	940	470	170.7	8.5	0.4
15-29-115-3W6	3500-4644	29	2215	12	690	345	0.6	10.2	0.5
5-28-115-4W6	4368-5205	5	166	3	60	30	153.3	3.6	0.7
12-24-82-6W6	4100-7079	19	1562	10	910	455	105.8	6.4	0.3
11-29-82-5W6	4100-7311	31	1182	19	570	285	104.4	10.7	0.6
3-21-112-6W6	4150-4802	6	146	2	40	20	159.0	0.9	0.2
13-35-112-10W6	4400-6200	22	948	13	360	180	150.8	11.4	0.9
3-1-119-9W6	4650-5774	18	2442	4	160	80	140.4	15.2	1.7
3-11-121-7W6	4800-5624	4	90	2	30	15	160.0	0.0	0.0
12-33-116-6W6	4250-5078	38	2385	8	180	90	140.7	20.8	2.2
14-36-116-6W6	4200-5300	4	146	3	80	40	37.1	13.0	2.1
14-9-118-8W6	648-6091	27	2238	4	140	70	141.3	11.9	1.4
9-15-118-8W6	5042-6142	8	256	3	130	65	128.7	0.8	0.1
2-36-118-8W6	4600-6135	10	628	4	140	70	153.0	9.6	1.2
5-33-109-8W6	692-6024	5	239	3	160	80	103.4	14.1	1.6
7-18RN-109-7W6	4800-5888	12	196	9	140	70	13.0	6.4	0.8
10-17RN-110-9W6	5400-6612	11	1350	5	360	180	47.3	11.5	0.9
2-20-81-9W5	4000-5848	7	620	5	330	165	115.3	0.8	0.1
4-20-81-9W5	622-5855	28	1730	17	990	495	123.1	8.7	0.4
5-3-81-9W5	3200-5871	20	1610	9	620	310	97.8	4.9	0.3
4-15-81-9W5	4900-5927	7	446	3	70	35	116.6	2.5	0.4
A9-5-82-9W5	5100-5590	4	98	3	40	20	67.1	5.0	1.2
3-32-34-8W5	4000-9430	15	3034	9	2020	1010	139.3	7.2	0.2
6-17-37-9W5	7100-10263	41	1866	39	1730	865	121.9	2.9	0.1
A2-13-34-11W5	UNSPECIFIED	9	182	7	128	64	138.3	5.8	0.7
7-17-33-7W5	794-8200	31	3460	17	2204	1102	136.3	13.1	0.4

is given as

$$Y = a_0 + a_1.X \qquad \text{------------------------------------3-14}$$

where a_0 and a_1 are obtained from the normal equations

$$\Sigma Y = a_0.N + a_1.\Sigma X$$

$$\Sigma XY = a_0.\Sigma X + a_1.\Sigma X^2 \qquad \text{------------------------------3-15}$$

which yield

$$a_0 = \frac{(\Sigma Y)(\Sigma X^2) - (\Sigma X)(\Sigma XY)}{N\Sigma X^2 - (\Sigma X)^2}$$

$$a_1 = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{N\Sigma X^2 - (\Sigma X)^2} \qquad \text{-------------------------------3-16}$$

a_1 is known as the regression coefficient of Y on X. In our case Y represents the azimuth of a breakout and X the depth. To evaluate the significance of a regression coefficient one must consider the scatter or spread of points about the regression line of Y on X. This is given by the statistic *Standard Error Of Estimate of Y on X.(Sy,x)*. Suppose we let Y_{est} represent the values of Y for given values of X as estimated from (3.14), then

$$Sy,x = \sqrt{\{\Sigma(Y-Y_{est})^2/\ n\}} \qquad \text{------------------------------3-17}$$

Equation 3-17 can be written as

$$S^2y,x = 1/n.(\Sigma Y^2 - a_0.\Sigma Y - a_1.\Sigma XY) \qquad \text{--------------------3-18}$$

This standard error of estimate has properties analogous to those of the standard deviation in the sense that if lines are constructed parallel to the regression line of Y on X at respective vertical distances Sy,x , 2Sy,x , and 3Sy,x from it, it is found (if n is large enough) that there would be

included between these lines about 68% , 95% , and 99.7% of the sample points respectively. Now that a least square regression line has been fitted to the points,we would like to know how well a straight line fits the points or describes the relationship between the variables. In other words we want to determine the goodness of fit of the line fitted to the data. The quantity which does this is the coefficient of correlation (r). r is a dimensionless quantity which varies between -1 and +1. If Y tends to increase as X increases we have a positive or direct correlation. If Y tends to decrease as X increases we have negative or inverse correlation. If r is near zero it means there is almost no linear correlation between the variables. r can be expressed in several ways but for computational purposes we write

$$r = \frac{N\sum XY - (\sum X)(\sum Y)}{\sqrt{\{N\sum X^2-(\sum X)^2\}\{N\sum Y^2-(\sum Y)^2}} \quad \text{------------------------- 3-19}$$

It is worth noting that a high correlation coefficient (i.e. near 1 or -1) does not necessarily indicate a direct dependence of the variables.

Tests of Hypothesis and Significance

In order for any test of hypothesis or rules of decision to be good they must be designed so as to minimise errors of decision. Obviously this is not simple at all since, for a given sample an attempt to decrease one type of

error is accompanied by an increase in other types of error. However, one type of error may be more serious than another which may call for a compromise in favour of a limitation of the more serious error. The only way to reduce all types of errors is to increase the sample size which may or may not be possible.

Level of Significance

Rejection of a hypothesis when it should be accepted is defined as *a Type I error*. Acceptance of a hypothesis which should be rejected is defined as *a Type II error*. In testing a given hypothesis, the maximum probability with which we wish to risk a Type I error is called the *Level of Significance* of the test. It represents the probability of our being wrong in rejecting the hypothesis.

The regression equation $Y = a_0 + a_1.X$ was obtained on the basis of sample data. We are often interested in the corresponding regression equation for the population from which the sample was drawn.

$$Y_{pop} = A_0 + A_1.X_{pop}$$

If we wish to test the hypothesis that the regression coefficient of the population A_1 is zero at some chosen significance, we use the fact that the statistic t has Student's distribution, with (n-2) degrees of freedom, where

$$t = \left((a_1 - A_1).Sx\right).\ (n-2)^{1/2} / Sy,x = (a_1 - A_1).\sqrt{\{(n-2)/(1-r^2)\}} \quad 3\text{-}20$$

Here Sy,x is the standard error of estimate of Y on X, Sx is the standard deviation of X, and r is the correlation coefficient. This fact can be used to find the confidence

intervals for population regression coefficients from sample values.

In applying Equations 3-14 through and including Equation 3-20 to our data we can then compare our t values to the Student's t-distribution table (given in many statistical text books), with the correct number of degrees of freedom, and find at what level of significance the hypothesis is to be accepted or rejected.

Table 3.3 presents regression results for 21 wells in which breakouts were measured over a depth range greater than 2000 feet. Column 3 shows values for the regression coefficient a_1 for the sample and column 4 gives the standard error of estimate of the azimuths on depths. Column 6 shows the various t-distribution values and column 7 shows the degrees of freedom which can be used to find the level of significance at which the test can be accepted by reading the appropriate t-value and degree of freedom from tables in text books. In column 5 we have the values of the correlation coefficient.

Results

It is clear that the regression coefficient a_1 is in all wells small enough to have arisen with more than 5 percent probability, in a population having $a_1=0$. Of the 21 wells listed in Table 3.3 , 10 have $a_1 > 0$ and 11 have $a_1 < 0$. We cannot reject the hypothesis that the azimuths of the breakouts are unrelated to depth and the variation observed with depth is only by chance

TABLE 3.3

Regression of breakout azimuths on depths showing the regression coefficients a_1 (deg/ft), the correlation coefficient r, the standard error of estimate Sy,x(deg), the t-distribution, and the degrees of freedom df. (Only wells with the entire breakout intervals extending through 2000 feet depth intervals are listed here).

Well	a_0(deg)	a_1(d/ft)	Sy,x(deg)	r	t	df
6-30-46-17W5	155.57	-0.00232	28.3	-0.183	-0.059	619
7-9-49-24W5	116.95	0.00112	45.7	0.087	0.038	1121
14-20-50-12W5	129.78	-0.00080	10.8	-0.052	-0.011	199
10-27-45-16W5	175.12	-0.00290	4.1	-0.460	-0.085	680
13-9-52-8W5	143.37	-0.00242	19.3	-0.203	-0.050	405
6-20-50-15W5	281.75	-0.01416	18.1	-0.475	-0.345	459
3-36-49-23W5	143.06	0.00042	28.7	0.062	0.018	1757
5-3-81-9W5	95.82	0.00046	10.5	0.024	0.008	308
4-20-81-9W5	122.32	0.00055	18.9	0.050	0.012	493
3-1-119-9W6	172.69	-0.01128	30.8	-0.489	-0.114	78
12-33-116-6W6	144.05	-0.00677	41.2	-0.269	-0.066	88
11-29-82-5W6	35.66	0.01150	20.2	0.356	0.200	263
15-29-115-3W6	153.81	0.00856	20.3	0.304	0.166	343
5-5-35-11W5	-289.62	0.02845	19.1	0.716	0.881	468
9-18-83-6w6	164.52	-0.00786	10.6	-0.306	-0.154	348
14-21-37-11W5	151.93	-0.00011	8.1	-0.037	-0.005	1838
2-29-59-22W5	113.99	0.00178	22.9	0.115	0.055	938
3-32-34-8W5	167.45	-0.00442	11.9	-0.446	-0.158	1022
6-17-37-9W5	130.71	-0.00105	5.5	-0.176	-0.031	863
A2-13-34-11W5	65.50	0.00553	14.5	0.194	0.044	62
7-17-33-7W5	72.14	0.01084	31.9	0.533	0.420	1073

IV. BREAKOUTS AND STRESS ORIENTATIONS IN THE WESTERN CANADIAN SEDIMENTARY BASIN

Relation of Breakouts to Location and Lithology

In Chapter III the statistical distribution of breakout azimuths has been set out. In most holes, azimuths are closely grouped together, as shown by the mean orientations of the various breakout zones within each hole (Table 3.1), and the standard deviations listed in Table 3.2. In the holes logged through a sufficient range of depth to allow investigation of regression of azimuth on depth, such regression is not significantly different from zero (see Table 3.3.). Figure 18 is a map showing how the azimuths change with location. The azimuth referred to is the representative azimuth of breakout for the well as a whole obtained by combining the various breakout azimuths in the well given in Table 3.2. The central dot shows the position of the hole and the mean orientation of the breakout is shown by the line through it. The number attached to the line is the mean orientation of the various sections in the well.

We now consider the relation of the breakout azimuth to the geological age (i.e. period), formation and lithology. These data are shown in Table 3.1 under the columns Formation (Fm) , Lithology (Lith), and Period (Age), and have been obtained from the sample descriptions for the wells. Sections under these columns which are blank indicate that the information was not available for those wells. It

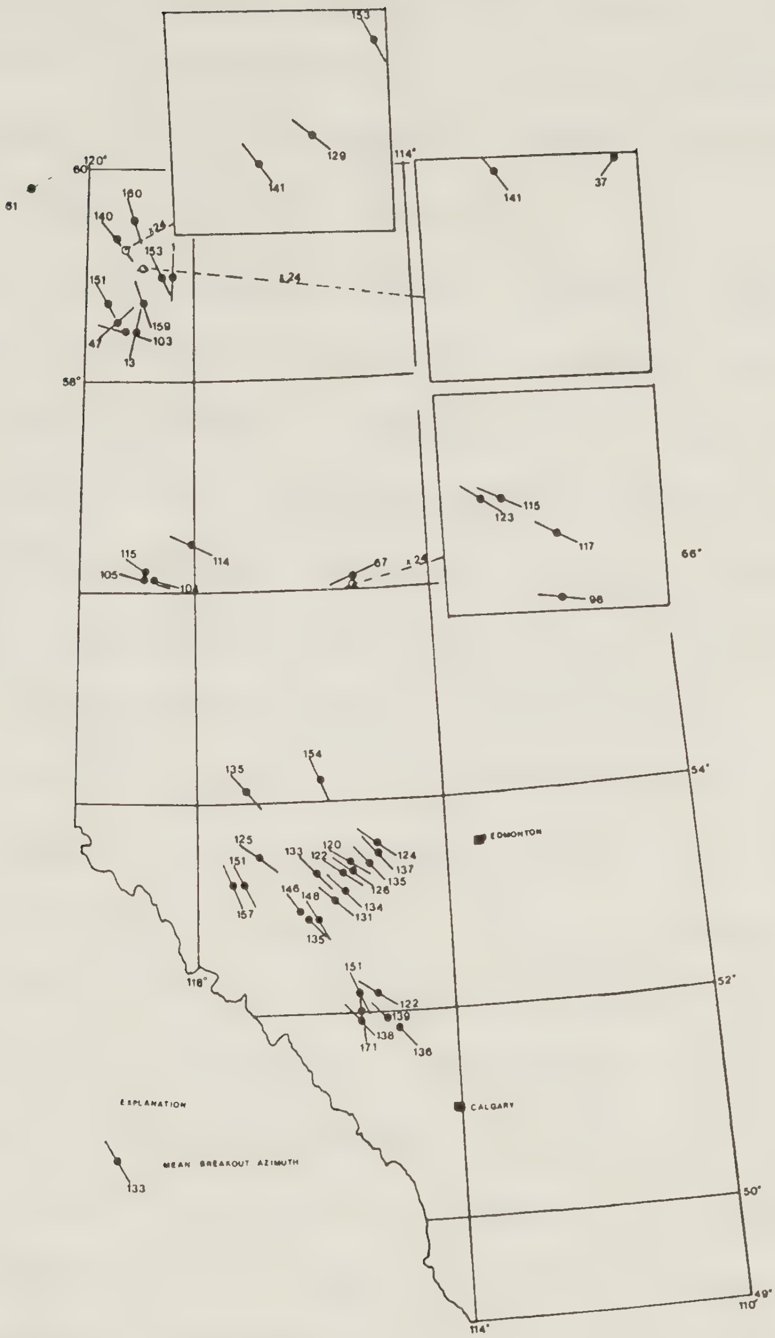


Figure 18.... Map of Alberta showing well locations and breakout azimuths

is evident, however, from these columns that breakouts have occurred throughout the sedimentary basins in rocks ranging from Devonian to Cretaceous in age. In some cases breakouts have been observed at different depth intervals running through the entire depth of the hole.

A look at the columns headed formation and lithology reveals many interesting points. Breakouts have occured in formations like Elk Point, Wabamun etc. in the Devonian right to Belly River and Bearpaw formations in the Upper Cretaceous period. Within a given formation some sections show breakouts but other sections do not, for reasons which are obscure. Breakouts may occur in any position such as the top, middle or bottom sections of the formation. The pattern does not appear to be regulated by the type of the lithology. A word of caution must be sounded here. The sample descriptions from which our stratigraphic information was obtained merely stated the predominant lithologies found and only stated the traces present but not the percentages of these traces. A knowledge of the percentages of such traces would be useful in view of the fact that there are several diagenetic processes involved in the transformation of unconsolidated sediments to consolidated sedimentary rocks. However, there are formations in which only one kind of lithology, without any traces, runs through the entire depth range in which breakouts occur in certain depth intervals separated by uncaved intervals.

Although the elongated sections which did not satisfy our three criteria for selecting a breakout are not included in Table 3.1, a careful study of the ages, formations, and lithologies of these zones was carried out. The entire study shows that breakouts are not lithologically controlled. They have occurred through most parts of the Western Canadian sedimentary basin cutting through limestone, dolomite, shale, sandstone, anhydrites, cherty shales, siltstone, and varying combinations of these sedimentary rocks. At the same time, the intervening zones without breakouts have exactly the same types of lithology as already listed. It can therefore be safely concluded that the breakouts and/or elongated zones are not significantly related to the lithology and age of formation. There is no evidence of any significant relation between breakout azimuths and the properties of the rock.

This agrees with the observation of Babcock (1978) on a smaller sample of breakout data. The logs used in this study give no indication of the dip angles of the various strata. This study therefore cannot add to the evidence given by Cox (1970) and Babcock (1978) that the breakouts and their azimuths are unrelated to the dip.

There are two wells included in this study in which the two breakout zones selected using the three criteria have azimuths approximately orthogonal to each other. These wells are included in Table 3.1. Some other wells have one or two intervals with breakout azimuths differing by as much as 90°

from the dominant azimuths. Such wells have not been referred to as bimodal wells. This study has shown that whatever their cause, a predominant direction of breakout is almost always present. Variations in this direction with position may represent local variations in the orientation of the horizontal stresses.

Pore water pressure P_w and the pressure P_m in the drilling mud which fills the hole were also disregarded in the discussion in Chapter II. These have no effect on the orientations of the fractures (Gough and Bell, 1982) nevertheless, they modify the magnitude of the stress differences. At points P and Q (p, q) of figures 12 and 13

$S_r = P_m - P_w$ and the tangential stress is

$S_\phi = 3S - s - P_w$ and $T_{r\phi} = 0$.

Thus the stress difference becomes

$S_\phi - S_r = 3S - s - P_m$.

The Mohr circle Fig. 10 contracts in diameter by P_m and moves to the left by P_w. P_w is often lithostatic and cannot be less than hydrostatic, so that P_m may often be comparable to P_w. The shear strength T_0 required to resist failure will be reduced somewhat as a result of the shift of the Mohr's circle to the left and the nature of the envelope. The shift of the circle to the left implies a reduction of the stresses, in a biaxial stress field, needed to cause failure.

Hydraulic Fracturing

In-situ measurement of stress by hydraulic fracturing can both provide the orientation and magnitude of the principal components of stress, if S_3 is not vertical (Kehle, 1964 ; Fairhurst, 1964), provided the fracture pressure, the instantaneous shut-in pressure (ISIP), the pore pressure and the tensile strength of the rock are measured. Hydraulic fracturing is a petroleum engineering technique carried out at depths of several thousand feet to stimulate production of oil bearing horizons. An understanding of the basic principles which govern the development of the fractures is a prerequisite to its successful application. It is assumed that the hole is drilled parallel to one regional principal stress usually the vertical stress S_v, which is assumed to be equal to the lithostatic load ρ.g.h. The stresses S and s normal to the hole axis are then the other two principal stresses and are horizontal. The pre-existing regional stresses produce stress concentration close to the borehole with the maximum value of (3S-s) and a minimum of (3s-S) in the tangential direction. The smallest tangential stress of (3s-S) at the ends of the diameter parallel to S may be greater than, or equal to, or less than zero depending on the S/s-ratio. If a section of the hole is sealed and pressurized to a pressure p, a second stress system will be superimposed on that just described. In the region close to the packers, Kehle (1964) assumed that the packers are held in place by a band of

uniform shear stresses and made an analysis to determine these stresses. His results indicate that high tensile vertical stress of the order of the applied pressure (-p) is induced in the immediate vicinity of the packers, and in about 80% of the central region of the interval a tangential tensile stress is generated. If however inflatable packers are used to seal the hole a normal pressure will be exerted resulting in a considerable reduction of the axial tension and will require a much higher pressure for the initiation of horizontal fractures. Before such high pressures are reached a fracture will be initiated vertically (Zoback et al, 1977). As the pressure in the hole is increased a fracture will be initiated at the wall of the borehole when the tension generated by the fluid is sufficient to overcome the combined effect of the regional compression (3s-S) and the rock strength. The plane along which a fracture will commence will be that across which the resultant of the effective compressive and tensile strengths are first reduced to zero. In the case of a smooth cylindrical wellbore this plane must be vertical and perpendicular to the least principal regional stress. If the vertical stress is the minimum principal stress a horizontal tensile fracture might be expected to form (Kehle, 1964; Hubbert and Willis, 1957) However, Zoback et al (1977) have argued against this. This contention of Zoback et al is supported by laboratory experiments reported by Haimson and Fairhurst (1970). Haimson (1976b) suggested that if $S_v = S_3$ then

induced fractures initiate in a vertical plane and then become horizontal as they propagate a few hole radii from the wall into the undisturbed regional stress field.

The breakdown pressure P_b is recorded. If the pump is shut off immediately and the hydraulic circuit is kept closed an instantaneous shut-in pressure, a pressure that is just sufficient to hold the fracture open, is recorded. The theory derived by Hubbert and Willis (1957) and Kehle (1964) for fracture around a pressurized borehole is used to relate P_b, the breakdown pressure, the instantaneous shut-in pressure ISIP, to the in-situ principal stresses and the tensile strength, T, of the rock. For a vertical borehole, the tensile fracture should be oriented in a direction perpendicular to s, the least horizontal principal stress, at least within the immediate vicinity of the borehole, and the magnitude of s is equal to ISIP. S, the maximum horizontal principal stress, is determined from the equation

$$P_b = 3s - S - p + T \qquad \text{-----------------------------------} 4-1$$

where p is the static pore pressure in the rock surrounding the borehole. T can be measured in the laboratory and p in the field. From the discussion so far it is clear that the hydraulic fracture will generally take place parallel to the maximum horizontal principal stress. Breakouts on the other hand occur parallel to the lesser horizontal principal stress or perpendicular to the larger horizontal principal stress. It is therefore, not surprising that fractures detected by the 4-arm dipmeter tool may occasionally show

two trends one being a major one, if mud pressure has occasionally produced inadvertent hydraulic fracturing.

The question to be asked will therefore be, how the hydraulic fracturing comes into play? Prior to the deliberate application of hydraulic fracturing by man, its occurence has been detected during water flooding and squeeze cementation processes. Rocks have been accidentally fractured during grouting treatments and when high specific gravity muds have been used in drilling wells. Furthermore, it has been observed (Von Schonfeldt and Fairhurst, 1969) that formations without any measurable permeability under natural conditions have a noticeable effect of rate of loading. At a low rate of application of pressure, the formation breakdown is lower than at a higher loading rate. Such a loading rate may be likened to the varying rate at which drilling is done depending on the commercial importance of the zone being drilled. Accidental hydraulic fracturing during the drilling stage with high specific gravity mud can therefore not be ruled out. It is worth mentioning also that although the vertical stress approximates the overburden, thus implying a reduced effect of accidental hydraulic fracturing, we should not lose sight of the fact that the oil wells are restricted to sedimentary layers. Sediments are sheet-like deposits of various competency stacked one upon another. Layered sequences of unlike materials transfer stress much differently than homogeneous and isotropic materials, a phenomenon known as

arching. Arching may also involve the reaction with time between beds of different competency and hence disrupts the uniform stress distribution with depth which is assumed under homogeneous and isotropic conditions. Such an effect creates regions of both high and low stress concentrations. As a result of the alteration of the stress distribution by arching we can expect that in the same oil field, for a given horizon breakdown pressure can vary significantly as evidenced by the results obtained in the Gulf Coast area where vertical fractures have occured at injection pressures far less than the total overburden pressure (Scotts, Bearden, and Howard, 1953).

Another point which may need examination is the assumption that one principal stress is vertical and that the borehole is drilled parallel to this regional principal stress. The assumption that the hydraulic fracture propagates perpendicular to the least principal stress (Hubbert and Willis, 1957) has been supported by agreement between hydraulic fracturing , geological and seismologically determined stress field indicators (Zoback and Zoback, 1980) However, McGarr and Gay (1978) found that in South Africa the directions of the most nearly vertical principal stress fall within a circle of 30° about the vertical. They also mentioned that stress measurements in deep mines in Canada, the United States and in Australia support significant departures from the assumption that one of the principal stress directions is vertical. This implies

that the two initially assumed horizontal stresses are not truly horizontal. Recognition of such a fact will also help in accounting for the irregular nature of fractures.

Breakout and Stress Orientations in Western Canada

Figure 19 shows the directions of the long axes of breakouts (or the direction of the least principal horizontal stress) and figure 20 indicates the inferred orientations of the maximum horizontal principal stresses for the results presented by Babcock (1978), by Gough and Bell (1981) and in this study, for the West Canadian Sedimentary Basin. It can be seen from this map that breakouts can serve as a useful method for mapping the various tectonic stress zones based on the stress trajectories in any given locality where directional spalling of the walls of a well are observed. The absence of significant variation of azimuths with depth, wherever these phenomena are observed, may imply that such large horizontal principal stresses are not necessarily limited to the top crustal sedimentary rocks but may be continued down into the deep and older Precambrian igneous rocks of the earth's crust

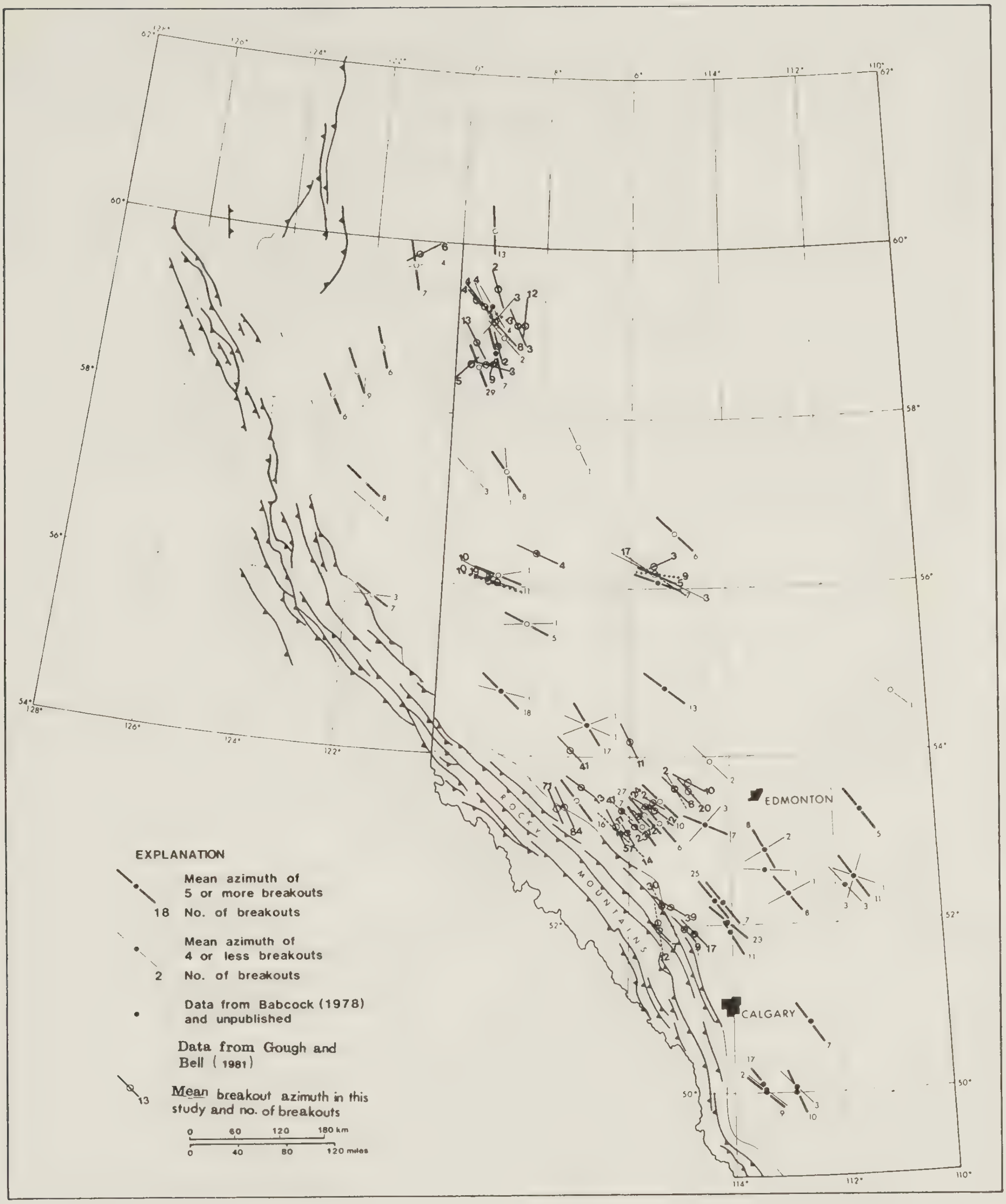


Figure 19.... Map of Alberta showing the orientations of the smaller principal horizontal stresses as inferred from the breakouts

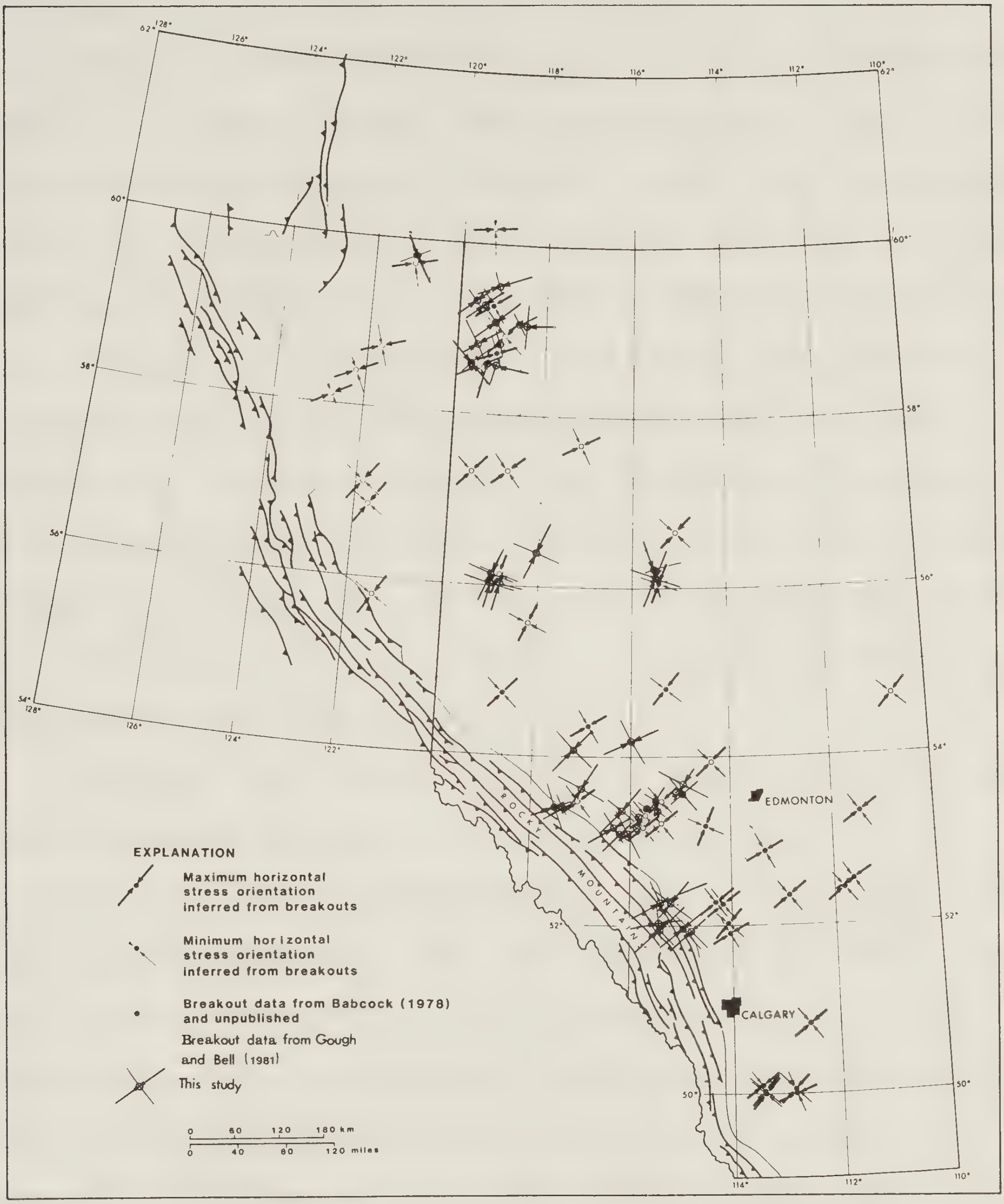


Figure 20.... Inferred directions of the larger horizontal principal stresses for the results presented by Babcock (1978), Gough and Bell (1981) and in this study

V. DISCUSSION

The Physical Significance of the Breakouts

Babcock (1978) concluded on the basis of his joint-sets study in Alberta (1973) that breakouts are a result of the drill encountering steeply dipping zones of pre-existing faults or joint-sets, which may or may not be open. Preferential breakage, in his view, is then controlled by a near-vertical joint which intersects the well and which in carbonate rocks may be solution-widened. In his view, the parallelism between azimuths of elongation and regional joint sets in Alberta and the consistency of the azimuths of elongation within, and between wells in varying lithologies all indicate an origin caused by the drill encountering a fracture or zone of fracture.

However, his study of joint-sets revealed four concentrations of joint directions on the surface, (NW, NE, N, and E). On a non-polar or axial data basis these four joint-sets directions may be represented as NW-SE, NE-SW, N-S, and E-W. Babcock's study of breakouts showed only one significant concentration of subsurface breakout direction that is NW or NW-SE. Bell and Gough (1979) argued that on Babcock's hypothesis the other joint directions would be expected to be represented in the breakout azimuths,but they are not. In addition Bell and Gough doubted that the joint directions at the present surface would necessarily be parallel to those at depths in excess of 2 km at which breakouts occurred, in view of the fact that sediments

involved in his study might have been laid down in varying tectonic settings between Devonian and Cretaceous times and that joints in general arise in several ways; such as soon after deposition of a sedimentary rock, or during later deformation, or as it undergoes erosion. These facts led Bell and Gough to put forward an alternative hypothesis to better explain the cause of breakouts and, perhaps, also the cause of surface joints of Babcock's System 1 (NE and NW strikes). They therefore proposed that in a general stress field, with large and unequal horizontal stresses, the holes themselves concentrate the stresses so as to produce subsurface breakouts with the breakout azimuth parallel to the smaller horizontal stress and normal to the larger horizontal stress. The analysis of such stress concentration by a circular hole was first found by Kirsch and has been discussed in chapter II.

From the present study, it is observed that the significant breakout azimuth or the preferred breakout orientation is SE, that is NW-SE when expressed axially. Thus only one of the four surface joint directions is significant, although a few breakout zones tend to show the NE or NE-SW strike. In short only the NW-SE set of Babcock's System 1 of surface joints is observed as breakouts. On Bell and Gough's hypothesis that breakouts are stress controlled, the observed irregularities have been fully accounted for. Babcock's hypothesis fails to explain why breakout azimuths do not exhibit the other surface joint directions. Babcock's

study also revealed that breakouts are unrelated to depth, lithology and the age of the formation. It is further observed by Babcock and in this study that breakouts are discrete, beginning and ending sharply, independently of depth, lithology and age of formation. It is very difficult to understand how breakouts can begin and end sharply, within and between formations, separated by similar lithologies with no regard to depth. In view of the various diagenetic processes involved in the transformation of the deposited sediments to consolidated sedimentary rocks from the Devonian to the Cretaceous age, which is more than 10^8 years, one wonders how surface joints can be a reflection of subsurface joints. In fact factors like cementation, compaction, recrystallisation, and many other processes involved in diagenesis coupled with the high temperatures and duration of the tectonic stresses will modify the response of the rock to stress, while any failure remains brittle. Such variables may lead to failure in some intervals in the sedimentary column, whereas the same material in adjoining area may not fail under the existing stress field. Consequently Bell and Gough's hypothesis can account for this discrete nature of breakout occurrence in wells. The presence of pre-existing fractures would also result in enormous circulation loss, which is however very small in this region. It is known that extensive circulation loss often leads to formation damage. Such damage often requires that hydraulic fracturing be carried out, this time

not just as a means of providing an increased permeability path into the otherwise tight formation, but as a means of creating a conducting channel through the damaged zones into the virgin formation. The absence of such effects as high circulation loss, damaged formation resulting from the drilling fluid escaping into the formation, and the complete absence of massive hydraulic fracturing processes in Alberta only go to support the point that pre-existing fractures of size as implied by Babcock are unlikely in the subsurface of Alberta. The only hydraulic fracturing process reported is the one at West Pembina (MacLeod, 1977). The fracturing direction is in agreement with the known theory on hydraulic fracturing and thus lends support to Bell and Gough's hypothesis (Gough & Bell, 1981). It is therefore, the present author's opinion that in the absence of positive extrapolation of surface joints to subsurface ones, Babcock's hypothesis does not account for the azimuthal alignment of breakouts. It is therefore concluded, subject to comparison with other stress measurement techniques in future, that breakouts are a result of the stress concentration by the borehole, in a general stress field having large and unequal horizontal stresses, at the walls of the hole resulting in the failure of some of the rocks. This is the hypothesis postulated by Bell and Gough.

Based on the Bell-Gough hypothesis, we find that the greatest horizontal principal stress trends N 25° E to N 60° E, with the majority occuring around N 42° E, and that the

least principal horizontal stress is directed N 30° W to N 65° W, with the majority around N 48° W throughout most parts of Alberta. Sbar and Sykes (1973) have reported the greatest principal horizontal compressive stress to be trending East to Northeast in Eastern North America and in the intermountain seismic belt in Montana, Idaho and Utah the minimum compressive stress trends East to Southeast. Our result thus fits closely to the general pattern of principal stress orientations reported in the older craton of the North American continent.

Implications of the Study

Measurement of stress by in-situ techniques can provide both the orientations and magnitudes of the principal components of stress. Such measurement of the stress field within the crust can provide, perhaps, the most useful information concerning the forces responsible for various tectonic processes, such as earthquakes. For example Sykes et al (1972) reported the occurrence of a series of small earthquakes generated in 1971 by the high pressure injection of fluids in a salt recovery well near Dale, about 10km east of Attica in Western New York State. When the high pressure injection ceased seismic activity dropped in three days from a rate of about 100 events per day to a rate of a few events per month. The triggering of the earthquakes was attributed to the increase of fluid pressure in the rocks under high tectonic stress. Healy et al (1968) also reported the Denver earthquakes. The Rocky Mountain Arsenal disposal well, which

was drilled through 3761 metres of sedimentary rocks of the Denver Basin near the city of Denver, Colorado, was intended for the disposal of waste fluids. The injection of fluid which was started from March 1962 to September 1963 was at a rate of about $2.1*10^7$ litres per month. Fluid injection ceased from October 1963 to August 1964, but was resumed under gravity from September 1964 until March 1965 at a rate of about $7.5 * 10^6$ litres per month. The rate was then increased to about $1.7 * 10^7$ litres per month until February 1966 when the exercise was terminated because of growing evidence of its connection with local earthquakes. Evans (1966) used the epicentral locations by Wang (1965) of earthquakes near the well and showed a correlation between rate of fluid injection and the earthquake frequency, with a lag of the earthquakes in the order of a few weeks behind the injection. The events which initially had epicentres less than 6 km from the well, were observed to continue with migration of the foci to the northwest. Healy et al examined the probability of a chance association, in both time and place, between the fluid injection and the earthquake swarm on the basis of the seismicity of the region and estimated this probability to be about 1 in 2.5 million. Healy et al (1968) therefore explained both the occurence of the northward migration and the occurrence of the three large earthquakes, among a series of earthquakes, of magnitude ≥ 5.0 to the outward diffusion from the well of a pressure front in the pore water. This diffusion would imply that the

volume of rock affected by the increased water pressure likewise grows and this increased volume is thus associated with the the large earthquakes in a large volume of major strain. But it is well known that the increase of the pressure of the water in pores and cracks produces no shear stress and therefore cannot cause an earthquake. The induction process of the observed earthquakes was attributed to the presence of a nearly critical initial stress which could eventually cause failure of rock by triggering through by increase of pore water pressure as the Mohr circle is shifted to the left. This explanation is based on the Mohr-Coulomb failure theory, and the Hubbert and Rubey hypothesis of effective stress (1959) (Healy et al, 1968; Gough and Gough, 1976; Gough, 1978).

The Rangely Experiment carried out by the United States Geological Survey at the Rangely Oilfield in Northwestern Colorado (Raleigh et al, 1972, 1976) was designed to verify quantitatively the explanation of the induced seismicity at Denver. There was an excellent agreement with the hypothesis. Raleigh et al (1976) also pointed out that this verification might have implications for the control of natural earthquakes at least in cases where it might be possible to pump water in and out of an active fault. This could possibly relieve the stress by first reducing the water pressure in wells at two points to strengthen the fault at those points, and then finally triggering an earthquake between the two points by injecting water there.

Knowledge of the state of stress is also critical to the design of underground excavations for mining and for nuclear waste disposal (Jaeger and Cook, 1969; Gough,1978). The massive hydraulic fracturing of formations in oil and gas fields to stimulate production is another field for which knowledge of the stress field at depth is very important. Application of stress measurements to the solution of problems in tectonics is not as straightforward as in engineering problems. The engineer is concerned with the stress field affecting the rock, whereas the geophysicist or geologist attempts to deduce the processes that might have caused the stresses. Thus the importance of the knowledge of principal stress orientations cannot be overemphasized. The use of breakouts to add principal stress orientations to the existing information on seismicity and tectonics will significantly increase the data base relevant to intra-plate earthquakes. Maps such as that shown in Figure 20 of the orientation of the horizontal principal stresses, will be of great value to engineering purposes and in addition will have important implications for the geophysics and structural geology of the area.

It must be emphasized that any attempt to relate the stress field to tectonic processes, must be based on a correct interpretation of the stress field. A variety of postglacial geologic features such as folds, faults, pop-ups, and other rock squeeze indicators may show high compressive stress in a region. Residual stresses may exist

in a rock according to its history of processes such as burial, lithification, denudation, heating, cooling, and past tectonic events and may persist to some extent after the rock is freed of boundary loads (Friedman, 1972). Such residual stresses may complicate the interpretation of stress observations. However, it would be difficult to attribute a consistently oriented stress field over a large area, as in the entire Western Canadian sedimentary basin, to residual stresses. The observed stress field almost certainly reflects tractions now acting on this part of the North American plate. The recent review by Zoback and Zoback (1980) shows that northeast-southwest horizontal larger compressions dominate the older craton of North America, as in the Northeastern United States (Sbar and Sykes, 1973) and the Western Canadian data fit well in this overall picture.

A knowledge of the orientation of the horizontal stresses is of great importance in the planning of a hydraulic fracture program. Near-surface ore bodies can be economically mined by open pit methods. Below the practical depth of open pit mining, new mining methods must be sought and developed to make deep ore bodies available to economic extraction. Solution mining has become a major method of extracting subsurface evaporite minerals because it is both economical and efficient. Hydraulic fracturing, apart from the fact that it is the only method currently in use that enables measurement of stress to be made at large distances

from a free surface, is used to develop permeable surface areas exposed to solvent for solution mining. Thus cross-connection of salt wells (and perhaps oil wells in future) by means of extending a hydrofracture from one well to the other has become a boon to the salt industry (Pullen Jr.,1958). The two wells so connected may be referred to as source and target wells, with the pressurized well from which the hydrofracture originates as a source. The target well acts in one of two ways. Ideally the target well should act like a sink so that the propagating fracture will want to intersect it. In some cases however, with the high stress concentrations around it, it may act as a barrier to the approaching fracture and most target wells act like minor sources, and thereby deflect the propagating fracture around themselves. To overcome this secondary role of the target well several techniques proposed have had promising effect. It will always be good practice to produce hydraulic fractures from the target well either before or during the major fracture attempt from the source,(Bays et al, 1960). Back fracturing has proved to be successful in several cases where a fracture connection was not successful in the original direction. It is also thought that much of the stress concentration around the target well might be reduced, if the target well were pressured up and held during the fracture operation of the source well, at a pressure less than the breakdown pressure. Crawford and Collins (1954) point out the adverse effects on the

efficiency of a fluid injection project when injection and production wells are not oriented with the natural and induced fractures. If wells are properly oriented and fractures of adequate length are induced, radial flow is reduced and areal-sweep problems are minimised.

We now consider the attempt to look critically at the lithologies in this study. The phenomenon of stress redistribution at depth in layered sequences of unlike rocks, known as arching, has been mentioned earlier. Arching may also be visualised in terms of massive competent beds acting as beams to carry the load imposed by crustal stress field and thereby reduce the stress on the less competent beds. Such an effect is important to the design of any subsurface opening. Perhaps the greatest importance of arching is its influence through the stress distribution on the breakdown pressure. The object of a multiple fracturing process (multifrac) is to obtain greater fracture area through closer fracture spacing, than could be obtained from the same number of wells with single vertical fractures. This method requires substantial deviation of the wells from the vertical and, therefore both the measured well length and drilling cost per unit length are increased when compared with a vertical well. Theory predicts a vertical hydraulically induced fracture in a strike-slip stress field, and such observations as are available confirm that in the Alberta sedimentary basin hydraulic fractures are generally vertical (Macleod, 1977). Thus it should be

possible to generate several fractures from a suitably deviated hole. Hydraulic fracturing theory predicts that fractures will propagate in a direction normal to the least principal in-situ stress or parallel to the maximum principal stress. Some experiments with non penetrating fluid indicate fractures may at least initiate parallel to the axis of the wellbore. A fracture initiated from an inclined open-hole wellbore might then result in a configuration unsuitable for the development of multiple vertical fractures. However, by casing the wellbore and perforating the casing over a small depth range, fracture initiation can be made to occur from a point or a small spherical cavity (Strubhar et al, 1975). The orientation should then be governed by the in-situ stress condition. Strubhar et al have shown experimentally that if the fractures are indeed oriented as dictated by in-situ stresses, the fractures will be sufficiently parallel and therefore be effective. The productivity index they found was two and three times that of a conventionally fractured well in the field.

Conclusions

It has been argued earlier in this chapter and elsewhere that the consistency of the breakout azimuths irrespective of depth, lithology and age of the formation in almost all the wells, and the fact that the breakout azimuths reflect only one out of the two joint systems of Babcock, lead to a safe conclusion that the breakouts are

stress controlled or possibly both.

It is probable that some of the deviations from the generally northwest-southeast orientation of the breakouts can be attributed to local stress anomalies and some also to accidental hydraulic tensile fracturing during drilling with high-density mud. Zoback and Pollard (1978) noted that although high viscosity fluid reduces fluid penetration into pre-existing fractures or into permeable rocks, it has the disadvantage that such fluid may lead to hydraulic fractures significantly in advance of the observed breakdown in the pressure-time history.

On the hypothesis that breakouts are stress controlled, the following conclusions can be made.

1. The state of stress in the earth's crust is not in general lithostatic. There are high horizontal stresses relative to the vertical stress irrespective of depth. Tectonic conditions and the various sedimentary layers may, however, influence this state of stress.
2. Perhaps, some horizontal fractures were wrongly taken for vertical ones. Such horizontal fractures are believed to result from local inhomogeneities like bedding planes, joint-sets and the phenomenon of arching.
3. Although breakouts tend to occur in preferential directions dictated by the orientation of the regional stresses, induced vertical fractures may also be expected to have a preferential direction. In most cases

this direction is not identical to that of breakouts, but at right angles to them.

Concluding remarks

The consistency of the data in this region of North America and elsewhere on the continent strongly suggests that this measurement does not merely reflect local stresses but does, in fact, reflect a regional pattern. The existence of high stresses is not confined to any member of the rock formations, nor to any particular age of the formations. The phenomena of high stresses exist elsewhere in the North American continent and the world (Sbar and Sykes, 1973; Hast, 1973,1974; Lo, 1978; McGarr and Gay,1978; Gough, 1978; Zoback and Zoback, 1980) as evidenced by features like breakouts, folds, postglacial faults,and pop-ups. These stresses are probably related to the current tractions on the North American plate in the overall context of plate tectonics.

BIBLIOGRAPHY

Aguilera, R., Van Poollen H.K. (May-June 1977). Current Status on the study of naturally fractured Reservoirs; *The Log Analyst* , 3-23.

Allaud, L.A., and Ringot, J. (1969). The High Resolution Dipmeter Tool; *The Log Analyst* , 3-11.

Anderson, E.M. (1951). *The Dynamics of Faulting and Dyke formation with applications to Britain.-2nd ed.,* Oliver and Boyd, Edinburgh. .

Babcock, E.A. (1973). Regional jointing in central Alberta; *Can. J. Earth Sci.* **10**, 1769-1781.

Babcock, E.A. (1974). Jointing in southern Alberta; *Can. J. Earth Sci.* **11**, 1181-1186.

Babcock, E.A. (1975). Fracture phenomena in the Waterways and McMurray Formations, Athabasca oil sands region, northeastern Alberta.; *Bull. Can. Petrol. Geol.* **23**, 810-826.

Babcock, E.A. (July 1978). Measurement of subsurface fractures from Dipmeter Logs; *Amer. Assoc. Petroleum Geologists Bull.* **62**, 1111-1126.

Barton, N. (1981). Hydraulic fracturing to estimate minimum stress and rockmass stability at a pumped hydro project; *Workshop on Hydraulic fracturing stress measurements, Monterey, California* , 1-15.

Bawden, W.F. (1981). Hydraulic fracturing in Alberta Tar Sand formations- A unique material for in situ stress measurements; *Workshop on Hydraulic fracturing stress measurements, Monterey, California* , 1-36.

Bays, C.A., Peters, W.C., and Pullen, M.W. (1960). Solution extraction of salt using wells connected by hydraulic fracture; *Amer. Inst. of Mining,*

Metallur., and Petrol. Eng.- Transactions 217, . .

Bell, J.S., and Gough, D.I. (1979). Northeast-Southwest compressive stress in Alberta: Evidence from oil wells.; *Earth and Planetary Science Letters* 45, 475-482.

Bredehoeft, J.D., Wolff, R.G., Keys, W.S., and Shuter, E. (1976). Hydraulic fracturing to determine the regional in situ stress field, Piceance Basin, Colorado; *Geol. Soc. Amer. Bull.* 87, 250-258.

Brown, Russel O. (1978). Application of fracture identification logs in the Cretaceous of North Louisiana and Mississippi; *Trans. Gulf Coast Assoc. Geol. Soc.* XXVIII, 75-91.

Brown, R.O., Forgotson, J.M., and Forgotson, J.M. Jr. (1980). Predicting the orientation of hydraulically created fractures in the Cotton Valley Formation of East Texas; *55th Ann. Fall Tech. Conf. and Exh. of Soc. Petrol. Eng., Dallas* , 1-12.

Coates, D.F. (1964). *Some cases in engineering work of orogenic stress effects, in Judd. W.R., ed., State of stress in the earth's crust*, Elsevier Press, New York. 679-688.

Coates, D.F. (1970). *Rock Mechanics Principles*, Supply and Services Canada, Ottawa, Canada. 874.

Cox, J.W. (May 1970). The High Resolution Dipmeter reveals dip related borehole and formation characteristics; *SPWLA Eleventh Annual Logging Symposium* , 1-26.

Crawford, P.B., and Collins, R.E. (1954). Estimated effect of vertical fractures on secondary recovery; *Trans. AIME* 201, 192-196.

Daneshy, A.A. (1971). True and Apparent direction of hydraulic fractures. (preprint); *Soc. Petrol. Eng. AIME.* SPE3226, 1-16.

Dresser Atlas (1974). *Log Review 1*, Dresser Atlas Division,

Dresser Industries, Inc., U.S.A.. .

Dresser Atlas (1975). *Log Interpretation Fundamentals*, Dresser Atlas Division, Dresser Industries, Inc., U.S.A.. .

Dusseault, M.B. (1977). Stress state and hydraulic fracturing in the Athabasca oil sands; *J. Can. Petrol. Technology* 16, 19-27.

Emery, C.L. (1964). *Strain energy in rocks in Judd., W.R., ed., State of stress in the earth's crust*, Elsevier Press, U.S.A.. 235-260.

Evans, D. (1966). Mountain Geologist; *J. Can. Petrol. Technology* 3, 23.

Fairhurst, C. (1964). Measurements of in-situ rock stresses, with particular reference to hydraulic fracturing.; *Rock Mech. and Eng. Geol.* 2, 129.

Friedman, M. (1972). Residual elastic strain in rocks; *Tectonophysics* 15, 297-330.

Gough, D.I. (1978). Induced seismicity; *The Assessment and Mittigation of Earthquake Risk.UNESCO* , 91-117.

Gough, D.I., and Bell, J.S. (1981). Stress orientations from oil-well fractures in Alberta and Texas; *Can. J. Earth Sci.* 18, 638-645.

Gough, D.I., and Bell, J.S. (1982). Stress orientations from borehole wall fractures with examples from Colorado, East Texas and Northern Canada.; *preprint* , .

Gough, D.I., and Gough, W.I. (1976). Time dependence and trigger mechanisms for the Kariba earthquakes.; *Engineering Geology* 10, 211-218.

Haimson, B.C. (1976b). The hydrofracturing stress measuring technique-method and recent field results in the U.S.; *Int. Soc. Rock Mech. Symp. Invest. Stress in Rock, Sydney Australia* , .

Haimson, B.C., Fairhurst, C. (1970). *In situ stress determination at great depth by means of hydraulic fracturing*, Elsevier Press, U.S.A.. 559-584.

Hast, N. (1973). Global measurements of absolute stress.; *Phil. Trans. Roy. Soc. Lond.* 274, 409-419.

Healy, J.H, Rubey, W.W., Griggs, D.T., and Raleigh, C.B. (1968). The Denver earthquakes; *Science* 161, 1301-1310.

Hepp, V., and Dumestre, A.C. (1975). Cluster - A method for selecting the most probable dip results from dipmeter surveys. (preprint); *Soc. Petrol. Eng. AIME.* , .

Herget, G. (1974). Ground stress determinations in Canada; *Rock Mechanics* 6, 53-64.

Hickman, S., and Zoback, M. (1981). On the interpretation of hydraulic fracturing pressure- time data for in situ stress determination.; *Workshop on Hydraulic fracturing stress measurements, Monterey, California* , 1-27.

Howard, G.C., and Fast, C.R. (1950). Squeeze cementing operations; *Trans. AIME.* 189, 53.

Hubbert, M.K., and Willis, D.G. (1957). Mechanics of hydraulic fracturing; *Petrol. Trans. AIME* 210, 153-166.

Hunter, Z.Z. (1956). 8 1/2 million extra barrels in 6 years; *Oil and Gas J.* 86, .

Imperial Oil Ltd. (1978). The Cold Lake Project.; *Report to Energy Conservation Board of Alberta* , .

Jaeger, J.C. (1956). *Elasticity, Fracture and Flow*, Methuen & Co. Ltd., London. 152.

Jaeger, J.C. and Cook, N.G.W. (1975). *Fundamentals of Rock Mechanics - 2nd ed.*, Chapman And Hall, London. 585.

Kehle, R.O. (1964). The determination of tectonic stresses through analysis of hydraulic well fracturing.; *J. Geophys. Res.* 69, 259-273.

Kirsch, G (1898). Die theorie der elastizitat und die bedurfnisse der festigkeitslehre.; *Zeitschrift des vereine Deutscher Ingenieure* 42, 797.

Lo, K.Y. (1978). Regional distribution of in situ horizontal stresses in southern Ontario; *Can. Geotech. J.* 15, 371-381.

Lo, K.Y., and Morton, J.D. (1976). Tunnels in bedded rock with high horizontal stresses.; *Can. Geotech. J.* 13, 216-230.

Mardia, K.V. (1972). *Statistics of directional data. Probability and Mathematical Statistics*, Academic Press, London and New York. .

McGarr, A. and Gay, N.C. (1978). State of stress in the earth's crust; *Ann. Rev. Earth and Planet. Sci.* 6, 405-463.

McLeod, J.G.F. (1977). Successful injection pattern alteration, Pembina J Lease, Alberta; *Paper presented at 28th Ann. Mtg. of Petrol. Soc. of Can. Inst. Mining* , .

Muraviev, V. (1975). *Operation of Oil and Gas wells*, MIR Publishers, Moscow. .

Nielsen, A.R. (1957). Cardium stratigraphy of the Pembina field, Alberta; *Soc. Petrol. Geol. Bull.* 5, 64-72.

Overbey, W.K. Jr. and Rough, R.L. (1968). Surface joint patterns prediction; *Oil and Gas J.* , 84-86.

Popov, E.P. (1978). *Mechanics of Materials - 2nd ed.*, Prentice Hall, Inc., Englewood Cliffs, New Jersey. 590.

Price, N.J. (1966). *Fault and Joint development in brittle*

and semi brittle rock, Pergamon Press, Oxford, London. 176.

Pullen, M. W. Jr. (1958). Method of mining salt using two wells connected by fluid fracturing; *U.S. patent no.2,847,202* , .

Raleigh, C.B., Healy, J.H. and Bredehoeft, J.D. (1976). An experiment in earthquake control at Rangely, Colorado; *Science* **191**, 1230-1237.

Roegiers, J.C., and McLennan, J.D. (1981). Factors influencing the initiation orientation of hydraulically induced fractures; *Workshop on Hydraulic fracturing stress measurements, Monterey, California* , 1-15.

Rose, C.W. (1951). Preliminary Report- Rock squeeze studies, Niagara River development; *Report, U.S. Army Corps of Engineers; Buffalo District, N.Y.* , .

Sbar, M.L., Barazangi, M. Dorman, J., Scholz, C.H., and Smith, R.B. (1972). Tectonics of the Intermountain seismic belt, Western United States: Microearthquake seismicity and composite fault plane solutions; *Geol. Soc. Amer. Bull.* 83, 13-28.

Sbar, M.L. and Sykes, L.R. (1973). Contemporary compressive stress and seismicity in Eastern North America: An example of intra-plate tectonics; *Geol. Soc. Amer. Bull.* **84**, 1861-1882.

Schafer, J.N. (1980). A practical method of well evaluation and acreage development for the naturally fractured Austin Chalk Formation; *The Log Analyst* **21**, 10-23.

Schlumberger (1970). *Fundamentals of Dipmeter interpretation*, Schlumberger Ltd. , New York. .

Scott, P.P. Jr., Bearden, W.G., and Howard, G.C. (1953). Rock rupture as affected by fluid properties; *Petrol. Trans. AIME* **198**, 111-124.

Spiegel, M.R. (1972). *Theory and problems of Statistics.*

Schaum's outline series, McGraw Hill Book Company,. New York. 359.

Strubhar, M.K., Fitch, J.L. and Glenn, E.E. Jr. (1975). Multiple vertical fractures from an inclined wellbore: A field experiment; *J. Petrol. Tech.* , 641-647.

Suau, J., and Gartner, J. (1980). Fracture detection from the logs; *The Log Analyst* , 3-13.

Sykes, L.R., Fletcher, P.J., Armbruster, J. and Davis, J. (1972). Tectonic strain release by fluid injection at Dale, New York; *Amer. Geophys. Union Trans.* 53, 524.

Timoshenko, S.P. and Goodier, J.N. (1951). *Theory of Elasticity. - 2nd ed.*, McGraw Hill, New York. 78-85.

Von Mises, R (1918). Uber die Ganzzahligkeit der Atomgewicht und Verwandte Fragen.; *Physikal. Z.* 19, 490-500.

Von Schonfeldt, H. and Fairhurst, C. (1969). Open hole hydraulic fracturing; *3rd Symposium on salt Cleveland, Ohio* 2, 404-409.

Zoback, M.D., Healy, J.H., and Roller, J.C. (1977). Stress measurements near Charleston, South Carolina.; *Trans. Amer. Geophys. Union* 58, 493.

Zoback, M.D., and Pollard, D.D. (1978). Hydraulic fracture propagation and the interpretation of pressure-time records for in-situ stress determinations; *19 th Symposium on Rock Mechanics, Lake Tahoe, California* , .

Zoback, M.D., Tsukahara, H. and Hickman, S. (1980). Stress measurements at depth in the vicinity of the San Andreas fault: Implications for the magnitude of shear stress at depth.; *J. Geophys. Res.* 85, 6157-6173.

Zoback, M. and Zoback, M.D. (1980). State of stress in the conterminous United States; *J. Geophys. Res.* 85,

6113-6156.

APPENDIX A

A. Properties Of $\bar{\varnothing}$

Let $\varnothing_1', \ldots\ldots, \varnothing_n'$ be the angles obtained from $\varnothing_1, \ldots\ldots, \varnothing_n$ when the new zero direction is α. Let

$\bar{C}' = 1/n \,.\, \Sigma \cos\varnothing_i'$; $\bar{S}' = 1/n \,.\, \Sigma \sin\varnothing_i'$ ------------------ A-1

We have $\varnothing_i' = (\varnothing_i - \alpha) \bmod 2\pi$. So that

$\bar{C}' = \bar{R}.\cos(\bar{\varnothing}-\alpha)$; $\bar{S}' = \bar{R}.\sin(\bar{\varnothing}-\alpha)$ --------------------- A-2.

If we write (A-2) as

$\bar{C}' = \bar{R}'.\cos\bar{\varnothing}'$; $\bar{S} = \bar{R}'.\sin\bar{\varnothing}'$ ---------------------------- A-3

then we have

$\bar{\varnothing}' = (\bar{\varnothing}-\alpha) \bmod 2\pi$; $\bar{R}' = \bar{R}$ -------------------------- A-4.

Hence Equation 3-2 is satisfied. Also from (3-4) and (3-5) we have

$\Sigma \sin(\varnothing_i - \bar{\varnothing}) = 0$ -------------------------------------- A-5

which corresponds to the equation in the linear case $\Sigma(X_i - X) = 0$, i.e.the sum of deviation about the mean vanishes.

Circular Standard Deviation

. We have seen that S_o lies in the range (0, 1). To relate S_o to the standard deviation on the line, it is natural to use the following result for the wrapped normal distribution.

$1-S_o = e^{-\sigma^2/2}$. We can then define the circular standard deviation as

$\sigma = \sqrt{(-2.\log_e(1-S_o))}$ ------------------------------ A-6

The range of is of course $(0,\infty)$. For small S_o, Equation A-6 reduces to $\sigma = (2.S_o)^{1/2}$. a transformation first suggested

by Von Mises, 1918).